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PREFACE

From the standpoint of the worker in the subject the object of a volume of this kind is to collect under one cover from sources more or less scattered the studies made by a group of investigators working in general from the same point of view and with similar technique and laboratory equipment. Such a compilation in part defeats its own purpose unless complete. We regret, therefore, to be compelled to omit from the initial volume so many of the studies issued from the laboratory during the period covered.

C. E. Ferree,
Director of Laboratory.

A NOTE ON THE DETERMINATION OF THE RETINA'S SENSITIVITY TO COLORED LIGHT IN TERMS OF RADIOMETRIC UNITS

By C. E. Ferree and Gertrude Rand
Bryn Mawr College

About a year ago[1] the writers undertook to determine the retina's sensitivity, relative and absolute, to colored light in terms of units that can be compared. Since several years will be required to complete this work, they have thought it best to publish a preliminary note showing briefly the purpose and scope of the investigation. The following points will serve to indicate what is being attempted in this study.

(1) All measurements of sensitivity will be made in radiometric terms. This will give an expression of the sensitivity of the retina in units which are directly comparable with one another. At present we have no direct estimate of the comparative sensitivity of the retina to the different colors further than is expressed, for example, by the relative width of the collimator-slit that has to be used to arouse color sensation when a light-source of a given candle-power is used. This kind of comparison is obviously unfair because such different amounts of energy are represented from point to point in the spectrum that a given width of slit would admit many times the amount of energy at one part of the spectrum that it would at another. In short, no adequate estimation and expression of the retina's sensitivity to color, comparative or absolute, can be made by means of the methods now in common use.[2]

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[1] The first public statement of our intention to use radiometric units in the investigation of the retina's sensitivity to color was made to the committee in charge of the Sarah Berliner Research Fellowship, February 1, 1911.

[2] Two criticisms have been received from private sources which it may be well to take account of here. In one the possibility of a point of view is implied, in the other a point of view is stated. The point of view, the possibility of which is implied in the first criticism, is that it is not proper to estimate the sensitivity of the retina in terms of physical units, because it is generally conceded by modern investigators of color vision that the retinal processes which transform the physical energy of the color stimulus into nervous energy is essentially chemical in its nature; and one can not assume that a certain amount of physical energy arouses an equal amount of chemical energy in the retina, or that equal amounts of physical energy arouse equal amounts of chemical energy. In answer to this, the writers would point out that these chemical substances are a part of the retina and their respective iner-

(2) Comparisons of results on many other points with such disparate stimuli seem equally inadequate: the relative time required for the different color sensations to attain their maximum of intensity, or retinal inertia; the relative rate of fatigue to the different colors; after-image and contrast sensitivity, etc.[3] In fact there is not a quantitative problem

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tias constitute one set of factors that determines the sensitivity of the retina to the different colored lights. It is not necessary to assume, therefore, that a given amount of physical energy arouses an equal amount of chemical energy, etc., in order to make our determinations of the comparative sensitivity of the retina to the different colors in terms of physical units. That would be necessary only if we were trying to separate out the nerve filaments, and to measure or compare their sensitivity to the different colors in terms of physical units. But even in chemical theories when speaking of the comparative sensitivity of the retina to the different colors, we do not mean the comparative sensitivity of the nerve filaments alone. We include the reaction of the chemical substances as well. Our contention, then, is that if the determination of the comparative sensitivity of the retina to the different colors is a proper problem, the determination should be made in terms of quantities that can be compared. This can be done either *a*, by using lights equalized in energy and determining by means of a sectored disc the relative amounts of these lights that are required to arouse sensation; or *b*, by using lights representing different amounts of energy and measuring directly in terms of radiometric units the amounts required to arouse sensation. We scarcely need point out that in speaking of the comparative sensitivity of the retina to the different colors we are not raising a new problem, but are merely recognizing a very old one.

The second criticism is in substance that a quantitative comparison of the effect of the different wave-lengths on the retina is improper because the different wave-lengths constitute stimuli too different in kind to permit of such comparison. This criticism we leave open, because we do not wish to discuss in this paper the propriety of the problem of comparing sensitivities.

[3] It is conceivable that two points of view may be held with regard to what is meant by after-image and contrast sensitivity. (1) After-image and contrast sensitivity may express a relation between the amount of light required to arouse after-image and contrast sensations and the unit of light used. (2) It may express a relation between the amount of light required to arouse the after-image and contrast sensations and the amount required to arouse positive sensation. If the former view should be held it will be convenient to start with stimuli equalized in energy, and to determine the relative amounts of light required to arouse the after-image or contrast sensation by means of a sectored disc. If the second view should be held, the energy of the lights used may first be rendered proportional to the sensitivity of the eye to the colors in question; and the liminal values may then be determined by means of the sectored disc. In each case the relative sensitivity may be expressed by the inverse ratio of the open to the closed sectors.

Similarly two views may be held with regard to the determination of the comparative rates of fatigue, and of the development-time of sensation. (1) Lights equalized in energy may be used. (2) The energy

dealing with the comparative functioning of the retina to the different colors in which there does not seem to be a need for the regulation and estimation of the stimulus in terms of a common unit of measurement. It is the purpose of the writers to extend the work as fast as possible into these related fields.

(3) We wish to make a careful study of the sensitivity of the peripheral retina, quantitative[4] and qualitative, in a large

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of the lights may be made proportional to the sensitivity of the eye to the different colors.

The need in both the above cases is equally great for a method of regulating and determining the amounts of light to be used in terms of a common unit of measurement.

[4] The following are two of the points we wish to take up: (1) A determination will be made of the ratio of sensitivity of peripheral to central retina from point to point for a single color in several meridians. This will show at what rate the retina falls off in sensitivity in a single meridian, and how uniform this decrease is in the different meridians. We have found in a preliminary study that this knowledge is greatly needed in explaining certain phenomena of the peripheral retina. Furthermore, when this determination is made for each of the colors with which we wish to work, the ratios of sensitivity for these colors at all the points can be calculated and a definite answer can be given to the question whether or not uniformity of ratio obtains throughout the retina. This question has been given considerable importance in the discussion of color theories. (2) The limits of sensitivity will be investigated. In general two problems are involved here. (a) The limits may be considered in relation to the comparative sensitivity of the retina to the different colors. (*b*) They may be considered in relation to existing color theories. In the first of these problems the limits should be obtained with stimuli equalized in energy. So obtained the results will constitute merely another expression of the comparative sensitivity of the retina to the different colors. The second problem is more complicated and will later be made the subject of a separate paper. A word indicating its relation to our present plan of work may, however, not be out of place here. It may be logically assumed, for example, that the Hering theory demands that wherever the blue-sensing substance is found, the yellow-sensing substance must also be found. We have no means of knowing where these substances are except by the sensations aroused. Speaking in terms of the theory, then, we have a right to assume that wherever the blue sensation can be aroused the yellow sensation should be able to be aroused also, provided a sufficiently intensive stimulus be used. If, therefore, in passing towards the periphery of the retina, a point be found where blue can be aroused and yellow can not, the evidence will be strongly in favor of the conclusion that no yellow substance is present, unless it can be shown that elsewhere in the retina so much greater energy of yellow light than of blue is required to arouse sensation that the amount needed for this far peripheral point is greater than can be obtained. To establish this point the comparative sensitivity to these colors would have to be obtained at various points in the retina. This would involve the determination of a ratio based upon the amounts of blue and yellow light required to arouse sensation. Two methods of measurement may be used. (a) The amounts needed may be measured directly by means of a thermopile of the type we use, or other sensitive radiometer. In a deter-

number of meridians. In general too much uniformity has been assumed with regard to the sensitivity of the peripheral retina. Generalizations of great importance to color theory have frequently been based upon the results of work in which careful investigation was made in only one or two meridians. The conception of stable colors, and its application in support of the Hering *Urfarben* may be taken as a fair example of a sweeping conclusion which is based upon work too limited in its range. With a careful standardization of factors, an investigation in any considerable number of meridians shows that stable colors do not exist.[5] Many other points of interest have come out in our more detailed study of the peripheral retina. For example, we find in the periphery of the normal retina small areas which are exact replicas of the Schumann case of color-blindness.

(4) We wish to conduct our investigation in full daylight instead of in the dark room. This is to eliminate the influence of the field surrounding the colored stimulus and of the pre-exposure. When the surrounding field is black, white is induced by contrast across the stimulus color. Since the colors all differ in brightness,[6] the induction takes place in different amounts for the different colors. This white, in proportion to its amount, reduces the action of the colors on the retina. Further, a given amount of white affects to different degrees the action of the different colors on the retina. To eliminate this twofold unequal action, the surrounding

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mination of limens the number of readings required would render this method tedious. (*b*) The energy of the two lights may be made equal by means of a thermopile and the final amounts required to arouse sensation may be secured by means of a sectored disc. From the ratio of open to closed sectors the amount the light is cut down in each case may be calculated and the ratios of energy may be determined from these amounts.

[5] The following points are offered in support of the above statement. (1) A red and green cannot be obtained which in every meridian of the peripheral retina will pass into gray without an intermediate change into yellow or blue. (2) The amount of blue that has to be added to a mixture of red and green to produce gray varies from point to point in a given meridian even where the extramacular region alone is considered. Further, a series of determinations made for a given meridian will not hold for the remaining meridians. (3) A red, green, and yellow can not be obtained which will not change in color-tone in passing from the center to the periphery of the retina in a single meridian.

Blue alone of the four principal colors is stable in tone for all parts of the retina.

[6] In a later paper one of the writers (Rand) will show that it is of no advantage to equate in brightness in determining the limits of color sensitivity, and that harm results in so many ways from the attempt to equate that it is doubtful whether it should be done even in determining the limens of color in the more sensitive parts of the retina.

field should be made in each case of the brightness of the color to be used. This can be done by working in a light room of constant intensity of illumination and making the surrounding field of a gray paper of the brightness of the stimulus color. In order to accomplish this, and at the same time be able to work upon any meridian of the retina we choose, we have constructed a special piece of apparatus which we call a rotary campimeter. The influence of pre-exposure is even more important than of surrounding field. If the pre-exposure is to black, white is added as after-image to the stimulus color. The effect of a black pre-exposure upon the stimulus color is greater than the effect of a surrounding field of black, because more white is added as after-image of pre-exposure than is induced by contrast from the surrounding field. This effect also can be eliminated only by working in a light room of constant intensity of illumination and by choosing as pre-exposure a gray of the brightness of the color to be used.

We began a quantitative study of the factors that influence the sensitivity of the retina to color three years ago. With the control of factors we had at that time, we could not, for example, duplicate by several degrees at any two consecutive determinations the limits of the zone of sensitivity to any color. The result of our study has been that we are now able with a given light-source to duplicate, within a degree, the results obtained at a previous sitting. We can also duplicate, almost as closely, the threshold values or the amounts of light required to arouse color sensation in the more sensitive parts of the retina. Details of this work will not be given here. They will appear in a series of papers to be published in the course of the present year.

Having completed our work of standardizing the factors extraneous to the source of light, we are trying now to secure a better control of the source. Standardization, so far, can be considered successful only with regard to the quality of the light. No adequate work has been done upon the standardization of the quantity of light. We believe this can be accomplished only by means of energy determinations. We expect to do our radiometric work by means of a surface thermopile (Coblentz model), and a DuBois-Rubens *Panzer-galvanometer*, unless future results show that some other combination of radiometer and galvanometer is more satisfactory.

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COLORED AFTER-IMAGE AND CONTRAST SENSATIONS FROM STIMULI IN WHICH NO COLOR IS SENSED

BY C. E. FERREE AND GERTRUDE RAND

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I. INTRODUCTION

In the March number of the PSYCHOLOGICAL REVIEW, 1907, Thompson and Gordon[1] describe a series of experiments in which colored after-images are obtained in the peripheral retina from stimuli in which no color was sensed. In the November number, 1905, and in the January number, 1908, of the same journal, Fernald[2] working under approximately the same condition reports similar results. In the *Proceedings of the American Philosophical Society*, 1908, however, Titchener and Pyle[3] deny the phenomenon, affirming their complete inability to get colored after-images when no color is sensed in the stimulus.

[1] Thompson, H. B., and Gordon, K., 'A Study of After-images on the Peripheral Retina,' PSYCHOL. REV., 1907, XIV., pp. 122–167.

[2] Fernald, G. M., 'The Effect of the Brightness of Background on the Extent of the Color Fields and on the Color Tone in Peripheral Vision,' PSYCHOL. REV., 1905, XII., p. 405; 'The Effect of the Brightness of Background on the Appearance of Color Stimuli in Peripheral Vision,' PSYCHOL. REV., 1908, XV., pp. 33–35.

[3] Titchener, E. B., and Pyle, W. H., 'On the After-images of Subliminally Colored Stimuli,' *Proc. of the Amer. Philos. Soc.*, 1908, XLVII., No. 189, pp. 366–384.

With regard to these discrepant reports, nothing more will be attempted at this place than to point out clearly the position held by each investigator. Titchener and Pyle contend that under no condition known to them can colored after-images be obtained from stimuli in which no color is sensed. Thompson and Gordon, and Fernald claim that under the conditions described by them, after-images may be obtained in which the color is clearly distinguished. The point at issue between them, then, is not whether the phenomenon can be gotten under this or that condition usually obtaining in the work on after-images, or under any given percentage of possible conditions, but whether it may be gotten by any experimental device whatsoever. Nor is it meant to extend the phenomenon to brightness sensation.[1] So far as the writers know, no one has ever claimed to be able to get an after-image from a brightness stimulus too weak to arouse sensation. The question, therefore, whether a subliminal sensory excitation can produce a supraliminal after-effect, considered in a general sense, is in no fashion under discussion. With the issue thus stated, the writers are impelled to take the affirmative side of the question by the experimental results they have obtained, and scarcely less strongly by theoretical considerations of the difference in the effect of different members of the brightness series upon all the colors when fused with them, and in the effect of a given brightness upon different colors. Working under the right conditions, the phenomenon is easily obtained. That its explanation is not essentially difficult will be shown in a later section of this paper.

The work on the peripheral retina has been repeated by the writers and the investigation extended to include other cases in which colored after-image and contrast sensations may be aroused by stimuli in which no color is sensed. It is the purpose of this report to describe these experiments and to explain the results obtained in terms of visual phenomena already known.

Before passing to a description of our own experiments it may be helpful to examine the work of previous investigators in

[1] For the sake of brevity, brightness is used here as a general term for the colorless sensation series, white, black and the grays.

order to determine from neutral ground if possible the cause of the disagreement in the results they have obtained.[1] In general two types of method have been used in arousing the color excitation. In one the color was kept below the limen of sensation by adaptation; in the other it was obscured by the action of an unfavorable brightness excitation. The former method was first used by Tschermak.[2] Tschermak's article is not a description of experimental work. It is an essay in which the author in part seeks to trace the analogies to visual adaptation found in the reactions of other tissue: muscle, nerve, secretory, etc., to external stimuli. The reference to the phenomenon we are discussing is very brief in this article and the description of the conditions under which it was obtained is quite inadequate to serve as a guide for future work. He says: "Haben wir doch gerade in der Anwendung des constanten Stromes auf Nerv und Muskel ein vorzügliches didaktisches Mittel, um die Grundbegriffe der allgemeinen Reiz- und Adaptationslehre zu veranschaulichen und einzuprägen. Am besten demonstrieren wir als Gegenstück zugleich die Wirkung eines mässig satten Farbglases auf das Auge: die Phase der Reizwirkung, individuell verschieden lang, und dadurch erinnernd an die verschiedenrasche Adaptation des Präparates vom Warmfrosch und Kaltfrosch an den constanten Strom—weiterhin das Stadium der vollendeten Adaptation, endlich den gegensinnigen Oeffnungseffect. Nicht minder lehrreich ist die Parallele des subjectiven und des objectiven Erscheinungsgebietes für das Phänomen des Einschleichens d. h. des Ausbleibens einer sinnfälligen Reizwirkung, wenn der Reiz so langsam anwächst, dass das Adaptationsvermögen folgen kann—gleichwohl hat auch nunmehr Wegfall des 'Reizes' eine gegensinnige Oeffnungswirkung. Analoges gilt vom Ausschleichen, also vom Ausbleiben eines sinnfälligen Oeffnungseffectes. Zum optischen Versuche schiebt man zweckmässig successive eine schwach tingierte Glasplatte vor die andere oder benützt einen Keil farbigen Glases."

[1] Because of the inadequacy of Tschermak's description of his method of working this can not be attempted for the work in the central retina.

[2] Tschermak, A., 'Das Anspannungsproblem in der Physiologie der Gegenwart,' *Archives des Sciences biologiques*, Sup. Band, 1904, XI., pp. 79–97.

In 1901 Titchener and Pyle carefully repeated and elaborated upon Tschermak's experiment on the central retina with entirely negative results. The writers can only commend the thoroughness with which they seem to have done this work. Their work on the peripheral retina is introduced with the following words. "We have already mentioned the experiments made by Titchener in 1906 with the view of testing the conclusions of Miss Fernald's first paper. The observations were rigorously confined to the black-white zone, and the outcome was definitely negative. In the meantime, however, the arousal of a colored after-image by a subliminally colored stimulus had been maintained for both the blue-yellow and the red-green zones. Unsystematic observations made in the Cornell Laboratory failed to confirm this result. It seemed worth while, however, to obtain further testimony; and Professor Baird, of the University of Illinois, very kindly consented to investigate the subject. The experiments were carried out by means of a simplified form of the Zimmermann perimeter, which permitted an accurate record of the degree of eccentricity at which the stimulus was exposed. Exploration was confined to the horizontal nasal meridian of each eye. The stimulus was a beam of light from an electric (16 c.p.) lamp, transmitted through appropriate combinations of gelatines and colored glasses; the colors employed were (non-equated) blue and yellow, red and green. Six of the most reliable laboratory students acted as observers, and Professor Baird had personal charge of the entire work. The after-images were projected upon white, gray and black grounds. The experiments proper were preceded by a careful determination of the outermost limits of color vision for the stimuli used, and all pains were taken to avoid chromatic adaptation" (pp. 376–377).

Professor Baird reports negative results in every instance. With regard to this work the writers can not help but observe that Baird has failed to conform to the conditions which Fernald had said are essential for getting the phenomenon. Without drawing upon their own experiments for a knowledge of essential conditions, they will point out three conditions which Baird has apparently failed to fulfill, the neglect of any

one of which is amply sufficient to account for his results being negative. (1) Fernald lays great stress upon the use of a campimeter screen by means of the induction from which the brightness conditions were obtained which obscured the color in her stimulus.[1] Baird used a simplified form of perimeter, how simplified Titchener and Pyle do not state. (2) Baird uses for the duration of the stimulation intervals of 30 to 40 seconds. Fernald is careful to state that the interval of stimulation should not exceed three seconds.[2] (3) In her description of conditions Fernald states that the color should be exposed behind the opening in a campimeter screen, and the card upon which the after-image is projected should be slipped in between the colored surface and the stimulus opening. Thereby the campimeter screen and thus the larger part of the field of vision remains unmoved and the least possible incentive is given for involuntary eye-movement. With Baird's apparatus, however, we would judge that the ground upon which the after-image was projected must have been moved in between the stimulus and the observer's eye, thus exerting a strong incentive to drag the fixation with it. A very slight eye-movement indeed is amply sufficient to blot out or to prevent from developing the instable peripheral after-image.

[1] While, as will be shown later in the article, the writers do not hold as Miss Fernald does that the inductive action of the campimeter screen is an essential or even a favorable condition, still they do insist that a campimeter screen or its equivalent is necessary in order to be able to give a projection field for the after-image without causing an amount of involuntary eye-movement that would prevent the momentary and instable peripheral after-image from developing.

[2] With regard to the importance of this point the writers are in entire agreement with Fernald. In fact one does not need to work long with peripheral after-images to be convinced that so long an interval as Baird used is absolutely prohibitive of colored after-images even when a less excentric portion of the retina is investigated than was the case here. A short interval of stimulation is necessary because of the rapid adaptation of the peripheral retina to color. It is well known that adaptation to color in any part of the retina takes place rapidly at first and then progressively more slowly until a stationary point is reached. Working in the central retina the writers have found a similar curve of effectiveness for after-images. After-images seem to occur most intensively when the stimulus is removed while adaptation is still going on. If one carries the stimulus beyond a stationary point in adaptation, the after-image will weaken roughly in proportion to the length of time during which the stimulus is regarded after the stationary point has been reached. This is true with both intensive and slightly supraliminal stimuli.

Failing to obtain the after-image in the central retina and to get confirmation by Baird that it may be obtained in the peripheral retina, Titchener and Pyle suggest explanations for the positive results gotten by Tschermak and Fernald. "The outcome of Tschermak's observations with the glass wedge must then in our opinion be explained by the prepossession of the observer and the roughness of the method employed. . . . It is less easy to account for the peripheral results." For a full statement of their explanation of the peripheral results the reader is referred to their article, pp. 378 ff. Brief mention only can be made of it here. We wish to comment on three points. (1) Their conception of the problem of getting color in the after-image when none is sensed in the stimulus is, we believe, different from that held and stated by Fernald. "The *experimentum crucis*," they say, "would be the production of a colored after-image in the achromatically adapted eye at a point lying well beyond the limits of blue-yellow vision." It is conceivable that two interpretations might be given to "well beyond the limits of blue-yellow vision." (*a*) The meaning might be well beyond the limits of blue-yellow vision whatever area and intensity of stimulus be used. And (*b*) it might be well beyond the limits at which these colors are seen when the stimuli used in the after-image experiments are employed. Wishing in every case to favor the point criticised, we choose the second interpretation. Thus to obtain a colored after-image well beyond the limits of blue-yellow vision would imply that a negative color excitation sufficiently strong to arouse sensation could occur in response to a stimulus which can under no condition arouse a positive color sensation. This is not at all the claim of Fernald nor of Thompson and Gordon as we understand their claim. They believe, in the cases cited by them, that the stimulus was prevented from arousing positive sensation by unfavorable brightness conditions. While it may not be clear from their work how these unfavorable brightness conditions prevent the positive sensation and permit the negative, there can hardly be any doubt that they would not claim that colored after-images can be aroused in the retina at a point "well beyond the limits of color vision." In fact in her

paper of 1905 Fernald specifically states that one should work just within the limits of color vision.[1]

(2) It is pointed out by Titchener and Pyle that the limits obtained by Miss Fernald show a considerable range of variability. The "*experimentum crucis*" thus has been inadequately performed. She has in reality obtained the after-image within the limits of blue-yellow vision. As pointed out in (1), this, we believe, is not the point at issue. The question is not whether the after-image can be obtained beyond the limits of color vision, but whether it can be obtained anywhere in the retina when color is not sensed in the stimulus in a percentage of cases large enough to preclude the possibility of its being due to chance happening, to error of observation, or what not. Apparently neither Fernald nor Thompson and Gordon, and certainly not Tschermak, have entertained the idea that the colored after-image can be obtained at any point on the retina where experiment shows that color can not be obtained in the positive sensation for the given stimulus under any conditions whatever.

(3) Titchener and Pyle quote the following observations furnished by Miss Fernald by private correspondence.[2]

[1] In her paper of 1908 Fernald states that the after-images are perceived most frequently just inside or just beyond the regular limits for the color. As compared with her first statement, this may seen somewhat loose and might lead to misunderstanding. There can be little doubt, however, that beyond the regular limits means for her beyond the limits obtaining for some given set of brightness conditions taken as standard—not beyond the limits for all brightness conditions. Fernald, it will be remembered, worked with very little control of the factors extraneous to the source of light that influence the sensitivity of the retina to color. The boundaries of her color zones thus varied within quite wide limits. In this region through which the boundaries of the zones varied, she was able to obtain color in the after-image when none was sensed in the stimulus. Her 'regular' limits fell somewhere within this region. She was thus able to obtain the after-image sometimes just within, sometimes just beyond the regular limits. She apparently never obtained the after-image at a point beyond her widest limits of sensitivity to a given color. The present writers, working with a control of brightness conditions that enabled them to duplicate their limits from sitting to sitting within a degree of variation, never obtained the after-image beyond the limits determined under their most favorable brightness conditions.

[2] A request was sent to one of the present writers (Ferree) to determine whether these after-images could be gotten, at the same time the similar request was sent to Dr. Baird. The results quoted are samples of the observations made at that time.

Observer: C. E. Ferree. Full illumination on bright day (May 17, 1908). Nasal meridian, right. White ground. Projection field white, except in obs. 14–17, when it was black. Stimulus, 13 sq. mm. Distance from eye to stimulus, 25 cm.

Fixation Point	Stimulus	Color Seen	After-image
80°	*O*	Dark gray	Unsaturated light blue
85°	*B*	Just dark	Wash of unsaturated yellow
85°	*Y*	Nothing	Nothing
80°	*Y*	Tinge of dirty yellow	Very pale blue
80°	Medium gray	Dark	White
80°	*O*	Indefinite gray	Nothing
80°	Light gray	Dark	White
75°	*Y*	Reddish yellow	Good blue
75°	*B*	Good blue	Good yellow
75°	*B*	Good blue	Good yellow
65°	*O*	Yellowish red	Unsaturated blue
65°	*Y*	Reddish yellow	Blue
60°	*G*	Indefinite greenish gray	Uncertain
65°	*G*	Greenish yellow	Dark red, more saturated than stimulus
80°	Medium gray	Dark	Nothing
80°	Medium gray	Dark	Nothing
65°	*G*	No color	Flash of red
65°	*R*	No color	Blue

Commenting on these observations Titchener and Pyle say: "Positive results occur in the first two and last two observations of the series. The former may be explained in terms of chromatic adaptation. If as the illumination suggests the observer began the work in yellow adaptation, the first blue after-image would naturally follow." If the above explanation were adequate, the blue after-image should have been obtained also when gray was used as stimulus. As a check experiment gray was repeatedly used as stimulus by Fernald, and in no case was the characteristic blue after-image obtained.[1] Furthermore the same yellow light which in terms of the explanation gave the stimulation for the blue after-image fell with undiminished intensity on the projection field, hence there was no shutting off and, since the projection field was white, even no diminution

[1] In a footnote p. 382 we find: "These observations were taken after the limits had been roughly determined in previous experiments. If the determination of limits was made at the same sitting, and if the last test color employed was orange, there would be additional reason for an initial yellow-adaptation." In reply to this we would say that in case of our own experiments orange and yellow were purposely not the last colors used in determining the limits; that had they been, abundance of time was given for the complete recovery of the eye before the after-image experiments were performed; and that if chromatic adaptation had been present, its effect should have shown in the after-image when gray was used as stimulus.

in the amount of the yellow daylight reflected to the eye for the period during which the after-image was observed. Thus no chance was given for a blue after-image to develop as the result of stimulation by the yellow in the daylight. Continuing Titchener and Pyle say: "If the second observation was taken at too short an interval of time the resulting blue-adaptation should show itself as a yellow after-image." We interpret this statement with some hesitation. It seems to mean that the first observation gave a blue after-image, and that if the second observation followed too closely upon the first, this after-image excitation in turn aroused a negative excitation which formed the physiological basis of the yellow after-image observed. If this interpretation is correct two conclusions would logically follow. (1) A negative after-image can itself give a negative after-image,—a phenomenon which, so far as the writers know, has never yet been observed. And (2) although a colored stimulus too weak to arouse positive sensation can not arouse a colored after-image, still the excess of yellow in clear daylight, which, reflected from the yellow stimulus, is too weak to be sensed as color, can arouse an after-image which not only can be sensed as color but which in turn can arouse a second after-image in which color can be sensed. "The two final observations suggest a shift of conditions. Green is seen at 65° as greenish yellow and at 60° as indefinite greenish gray. It is possible that in the case in which 'no color' is reported the green simply escaped notice; peripheral colors at the limit of vision often appear as momentary flashes. Again red is reported at 65° as 'no color' although reddish yellow had been seen as far out as 75°. It is possible that the flash of red escaped notice; it is also possible that red-adaptation from the preceding after-image brought out the blue." With regard to the possibility of the red and green escaping notice, the following points may be noted. (1) The stimulus color in this region of the retina has not so much a momentary character as the after-image color and would, therefore, not be so likely to escape notice as the after-image color. (2) The observations quoted above were made by one of the writers (Ferree), who here positively asserts that to the best of his knowledge this

was not the case. (3) In our own experiments to be described later in this article, conditions were obtained under which the after-images of red and green were obtained in practically 100 per cent. of the observations made. It seems scarcely possible that the color should have escaped notice in the stimulus in all of these cases and have been observed in the after-image. In case it be held that "red-adaptation from the preceding after-image brought out the blue," we are again asked to accept the thesis that an after-image excitation may in turn give rise to an after-image excitation strong enough to be sensed as color.

II. Cases in Which After-Images and Contrast Sensations are Aroused by Retinal Excitations Which Do Not Directly Condition Sensation

1. *After-Images*

The problem presented is: Can the color in a stimulus be obscured directly for sensation, and still set up an excitation upon the retina which will give an after-image? Our answer is that it can be done both in the central and the peripheral retina, but possibly more readily in the latter than in the former. To accomplish it, an experimental condition must be devised which will work against the color in the stimulus and relatively favor it in the after-image. A working principle is found in the difference in effect of brightness changes upon the saturation of the colors.

This effect may be expressed as follows. (1) Brightness fused with color inhibits the color sensation. With the exception of the region just within the limit of sensitivity for two colors,[1] the following may be stated roughly as the law of this action for all colors for all parts of the retina. White inhibits

[1] Over a region 3° in width just within the limits of sensitivity as determined with the Hering pigment papers at full illumination, red and yellow have a higher limen in black than in white. In this zone red and yellow darken as compared with their brightness values in the central and paracentral retina. Added to the black of the disc, then, we have the black due to the darkening of the color. Thus the figures which are read from the disc do not express the actual amount of black added to the color. Whether or not we have an exception here to the law of the action of brightness upon color which obtains in the rest of the retina is thus open to question. At least, the exception as expressed by the measurements is exaggerated.

most, the grays in the order from light to dark next, and black the least. (2) A given brightness change does not affect all colors to the same extent. If local and towards either black or white, blue and green lose their saturation completely before red, orange, and yellow; when the change is general and toward black, produced by decrease of illumination, yellow, red, and dark orange are obscured before green and blue. All of these changes were utilized at different times in our experiments both on the central and peripheral retina. It is readily seen that the technique of getting a colored after-image from a stimulus in which no color is sensed becomes merely a matter of fusing the least favorable brightness quality with the stimulus color and the most favorable with the after-image color. When this technique was carried out in its best form, the colored after-image was obtained in practically every case.

i. In Central Vision

Two methods of working were used in these experiments, one in which the brightness control came through changes in the general illumination of the field of vision, and the other in which the changes were local. The former method will be described first.

After-images were obtained of red, yellow, and orange stimuli of the Hering series of colored papers. The work was done in a long narrow dark-room with a small window at one end near the center, darkened by a solid and carefully padded door. By opening and closing this door, the general illumination of the room could be varied at will. The observer was seated in front of the window and to the left, so that the light coming in from above and behind fell free from shadow upon a screen placed in front of him.

The intensity of the stimulus was decreased by decreasing the illumination. Two methods were used in doing this, differing in the amount of dark-adaptation the eye had experienced before the stimulus was given. In the first, a preliminary determination was made of the illumination at which the stimulus was sensed as colorless. The experiment was then conducted at that illumination. The stimulus was exposed

from 5 to 15 seconds, varying with the subject, and the after-image observed. In the second method, the experiment was started at full illumination. The door was opened and the stimulus covered with a card of the same gray as the background. The door was then closed rather quickly until the point was reached at which the color is unperceived, this point having previously been carefully determined. The stimulus was exposed before the eye had become adapted to the decreased illumination, and the after-image was observed. The advantage of the second method is that with it the eye loses its sensitivity to color at a more intensive illumination than when the first method is used. That is, the eye gains in sensitivity to color at any point in a series of decreasing illuminations if it is allowed to adapt to that illumination before the exposure is made. Thus, by taking advantage of the lessened sensitivity of the eye to color with decreased illumination before adaptation sets in, we were able to work at an illumination that gave a stronger objective stimulus, and was more favorable for the development of the after-image. Either method, however, gave us unmistakable color in the after-effect. In order that we might be sure that the observer worked with stimuli in which the color could not be sensed and that color really was distinguished in the after-image, he was in the first place kept in ignorance of the color that was to be used in a given test, and in the second place was given at intervals in the series a gray for stimulus which could not be distinguished from the color at that illumination. Thus having run blank tests, and having used every precaution known to us to eliminate the influence of expectation, etc., we feel a reasonable degree of confidence in the results obtained.

The after-images gotten in this way in central vision are not so saturated as those obtained in peripheral vision, but in proportion to their saturation last much longer than peripheral after-images. The after-image of red shows greatest saturation, dark orange next, and yellow least. As one would expect from its quicker rate of adaptation and from the fact that after-images decrease in intensity after the stationary-point in adaptation is reached, the time of stimulation most favorable for

producing the after-image was shorter for the red stimulus than for the other colors. The time for orange was next shortest, and for yellow the longest.

Local changes in the brightness of color may be produced by objective mixing, by contrast, and by after-image. Of these three methods the addition of brightness as after-image is by far the most successful. By objective mixing the amount of colored light coming to the eye is reduced in proportion to the amount of brightness added. The color thus loses saturation from two causes: the reduction of the amount of colored light coming to the eye, and the inhibitive action of the brightness excitation upon the color excitation. For our purpose, it is of advantage to obtain the loss in saturation without any reduction of the amount of colored light coming to the eye, *i. e.*, by means of the inhibitive action of the brightness excitation alone.[1] This can be done by the addition of the brightness either as contrast or as after-image. Of these two, the after-image method yields the better results, as much more brightness can be added as after-image than can be induced as contrast. This is especially true of the central retina. The amount of inhibitive action that can be obtained by this means may be shown as follows. The limen of Hering red in a gray of its own brightness is for one observer 27°. When the after-image obtained by a stimulation of 10 seconds to black is projected on this color, the limen is raised to 60°. This after-image decreases in intensity very little for the first 8 to 10 seconds, and disappears after from 12 to 15 seconds. 10 to 12 seconds stimulation to color is quite sufficient to arouse an intensive colored after-image. Hence by a preëxposure of 10 seconds to black and by the projection of the after-image upon a colored stimulus, it is possible to keep the color in a fairly intensive colored stimulus below the limen long enough to arouse the excitation necessary to give a colored after-image of considerable intensity.

The method of working is as follows. A small colored disc composed of sectors of the color to be used and a gray of the brightness of this color, is set up on a color-mixer. A second

[1] As will be shown in a later paper, this action inhibits the effect of the color excitation, although it does not reduce its power to arouse after-image and contrast.

disc of black of the same dimensions is set up beside it. As much color is put in the first disc as will be rendered just subliminal by the after-image obtained by a 10 second stimulation to the black disc. The colored after-image is then projected on a black field. The addition of white to the stimulus works against its color, and the black projection field favors the color of the after-image. Proceeding by this method, a colored after-image of good saturation and duration can be obtained in every case. The method can be made still more effective by adding the brightness to the stimulus color by both contrast and after-image. For example, the colored disc may be exposed through an opening in a black screen. The white induced by this screen would then add to the effect of the white after-image and in consequence still more color may be used as stimulus without arousing a color sensation.

ii. In Peripheral Vision

The color in the stimulus may be obscured in three ways. (*a*) It may be carried to the peripheral retina near the limit of sensitivity for the color used and a brightness be induced across it that works against its saturation. (*b*) The unfavorable brightness may be mixed with it as after-image aroused by preëxposure to a brightness stimulus. (*c*) The stimulus may be carried to some angle of indirect vision not too remote from the fovea and the general illumination be decreased until the color is lost. In (*a*) and (*b*) the brightness is mixed with the color by contrast and after-image rather than added to it on the color-wheel or by some other means of objective mixing, because, as stated before, objective mixing decreases the physical intensity of the stimulus. This would decrease the energy of the positive color excitation, which would in turn decrease the energy of the negative excitation, and thus defeat the purpose of the experiment. But the addition of the brightness as contrast or after-image does not affect the energy of the stimulus; and while it reduces the effect of the positive excitation upon sensation, it apparently does not decrease its energy as retinal excitation, for it does not lessen its power to arouse after-images. This strongly indicates that the action of bright-

ness upon color takes place at some physiological level posterior to the seat of the positive and negative color processes, as will be shown in the next paper of this series.[1] Consider method (*b*) for example. Here the brightness is added as after-image. Its effect is to blot out the weakly supraliminal color in the stimulus, but it does not prevent the complementary color from appearing in the after-image. This is readily explained in terms of the above hypothesis as to the level at which this action takes place. If, as we suppose, the inhibition takes place posterior to the level of the positive excitation, the negative excitation is not weakened thereby. And since the brightness after-image which was added cannot itself leave behind a brightness after-excitation, nothing is carried over to the negative color excitation to weaken its effect upon sensation. Hence by this method of working we should get as much color in the after-image as if no brightness quality had been added to the colored stimulus.

While method (*a*) can also be used to obscure the stimulus color, still it is not so effective as (*b*) for obtaining the colored after-image; because (1) by means of it the zone of sensitivity cannot be narrowed nearly so much as by (*b*), and (2) the inducing field throws by contrast the same brightness quality across the after-image as it does across the stimulus, and so, roughly speaking, it inhibits the after-image as much as it inhibits the stimulus.[2] In fact, in the way it has to be used in the peripheral retina method, (*a*) alone is of little use in getting our phenomenon. To make this method work successfully, some means would have to be devised for changing the quality of the inducing surface in the interval between the end of the stimulation and the beginning of the after-image. That is, the stimulation would have to be given on a field which induced a brightness quality unfavorable to the saturation of its color,

[1] See 'An Experimental Study of the Fusion of Colored and Colorless Light Sensations: The Physiological Level at which this Action Takes Place.' (In press.) See also abstract in *Journ. of Phil., Psych., and Scientific Methods*, 1911, VIII., p. 294.

[2] The second objection to this method does not apply to the use of the contrast method in the central retina (see p. 207), for in the central retina the colored after-image is sufficiently stable and durable so that an entirely new projection can be substituted for the screen which induces the contrast. In this case the effect of the induction of this screen can be eliminated from the after-image.

and the after-image observed on a field whose inductive action was favorable to the saturation of its color. This change of the inducing field, however, can not be made for two reasons. (1) The duration of the peripheral after-image is very short. It comes as a momentary flash of color immediately after the stimulus light is shut off, and disappears before a change in the inducing field can be made. And (2) the after-image would be completely extinguished by the eye movement set up by shifting so large a part of the field of vision.[1]

The investigation of favorable conditions was conducted in part by means of the vertical campimeter and in part by means of the rotary campimeter.[2] The campimeter provides three possibilities for the variation of brightness conditions which was needed in our problem. By means of it, the brightness of the local preëxposure, the brightness of the inducing field, and the brightness of the field on which the after-image is projected may be changed at will. The brightness of the local preëxposure and of the field on which the after-image is projected may be varied by changing the cards held in the frame behind the stimulus opening in the campimeter screen. The brightness of the inducing field may be varied by changing the paper covering the campimeter screen. All of these variations were used in our investigation. Fernald recognized the influence of only two of these variations: the campimeter screen and the projection field.[3] And of the two the importance of campimeter screen was very much overestimated, while the impor-

[1] See Ferree, C. E., 'The Fluctuation and Duration of the Negative After-image,' *Amer. Jour. of Psychol.*, 1908, XIX., pp. 68, 87–97.

[2] For a description of the vertical campimeter see Fernald, G. M., 'The Effect of the Brightness of Background on the Appearance of Color Stimuli in Peripheral Vision,' Psychol. Rev., 1908, XV., pp. 27–29. For a description of the rotary campimeter see Ferree, C. E., 'A Description of a Rotary Campimeter,' *Amer. Jour. of Psychol.*, 1912, XXIII. (In press.)

[3] The influence of preëxposure under the ordinary conditions of working was apparently not at all realized by her. Her preëxposure and projection field were in most cases made of the same brightness as the campimeter screen. No reason is assigned for doing this. Some indication of her reason may perhaps be had from Thompson and Gordon who also use a preëxposure and projection field of the same brightness as the campimeter screen. They say: "When the stimulation had lasted the desired time, the screen was again put over the color, thus making with the campimeter a uniform gray surface upon which the after-image could be observed" (Psychol. Rev., 1907, XIV., p. 124).

tance of projection field was relatively underestimated. Moreover she seemed to entertain no clear notion of just how these factors produce their results. For example, the brightness induced by the campimeter screen was supposed to contribute in some fashion to the production of her phenomenon by working against the color in the stimulus and favoring it in the after-image; but just how it operates to do this was left in question. Apparently she had made no quantitative study of the fusion of brightness with color and of the relative influence of the different brightness qualities upon the saturation of color. From the side of explanation, then, she can scarcely be regarded as having a definite point from which to start.

Since the writers report the after-image in so much greater percentage of cases than Miss Fernald, and differ from her so much in their explanations of results, it may be well to discuss her work at this point in greater detail.[1] They have the following comments to make on her general technique and her explanation of how it produced the results she obtained.

1. No systematic attempt was made to determine the factors influencing her phenomenon. Of the full list of achromatic factors, for example: brightness of the surrounding field, brightness of the preëxposure,[2] brightness of the projection field, and the degree of general illumination, she recognizes only brightness of the surrounding field, brightness of the projection field, and the degree of general illumination. Especial stress is laid on the brightness of the surrounding field. As we have already shown, the influence of brightness of surrounding field is comparatively insignificant because it is exerted both upon the color of the stimulus and the color of the after-image. Thus if it is unfavorable to the one it will also be unfavorable to the other. It has a margin of influence, however, due to the fact that it does not act with equal strength upon the stimulus and the after-image. Its action is unequal because stimulus and after-image differ both in color and brightness. There would be on this account a small difference in the amount of induction by the screen in the two cases, due to the difference between the brightness relation of stimulus to background and that of after-image to background; and further a probable difference in the

[1] Fernald's work rather than Thompson and Gordon's is singled out at this point because Fernald has made a more extensive investigation of the brightness factors and their relation to the phenomenon in question than have Thompson and Gordon.

[2] Miss Fernald always used some kind of colorless preëxposure, but apparently she did not recognize its importance as a brightness factor. For her the preëxposure card served in the main merely as a neutral covering for the colored stimulus until a steady fixation could be obtained and the observer be otherwise made ready for the exposure to color. Towards the end of the work reported in 1909, however (p. 29), she apparently began to realize that if the fixation were held for a period varying from three to ten seconds, the preëxposure card would give a brightness after-image which would mix with the stimulus color and lighten or darken it, as the case might be. But under the ordinary conditions of working, she took no account of it as a brightness factor.

inhibitive action of this induced brightness upon the color, due to the fact that the stimulus and after-image are different colors. The factors of predominant importance are the brightness of the preëxposure and of the projection field. These are of greater importance (*a*) because more brightness influence can be exerted by means of them; and (*b*) because their action is more differential, *i. e.*, the brightness of the preëxposure acts upon the stimulus alone, and the brightness of the projection field acts upon the after-image alone. The brightness of the preëxposure can thus be made to work against the color in the stimulus and to have no effect upon the color in the after-image, and the brightness of the projection field can be made to favor the color in the after-image and to have no effect on the color of the stimulus.

2. No attempt was made to separate the achromatic factors and to study directly the relative importance of their effect upon the frequency with which the after-image may be obtained. However, in her study of the effect of achromatic conditions upon the limits of color sensitivity and upon color quality in stimulus and after-image, some attempt at separation was made, and in these experiments the observer was required to report cases in which color was sensed in the after-image when none was sensed in the stimulus. In order to study the effect of a given factor, the influence of all the factors but the one to be studied should be eliminated from the conditions of the experiment. If, for example, it were wanted to study the effect of the projection field, a gray of the brightness of the colored stimulus should have been chosen for the campimeter screen and preëxposure. In no case was this method of working employed. In her experiments to determine the effect of projection-field[1] the following conditions were used: The campimeter screens were platinum white, and black; the projection fields for each screen were in turn of black, white, and medium gray; and the preexposure was in each case of the same brightness as the projection field. Since neither the preëxposure nor the screen was chosen of the brightness of the colored stimulus, all the factors were present in each case, instead of one. And in her experiments to determine the effect of surrounding field, screens of white, black, and gray of the brightness of the color were used with preëxposures and projection fields to match the screen in each case. In this case also it will be observed that when the brightness of the screen was varied the influence of neither of the other two factors was ruled out.

3. Her statement of the most favorable brightness conditions for getting the after-image is in complete contradiction to all we have been able to find out directly concerning the phenomenon, or to infer from our investigations of the action of brightness upon color either in the positive sensation or in the after-image. For example, she states that white campimeter screen and a white projection field give the most favorable conditions for obtaining after-images of blue and yellow when no color was sensed in the stimulus. Stating her most favorable conditions for the after-images of red and green, she says: "In several instances in our later work a red after-image has followed an unperceived green when the stimulus was given on a white background and the dark screen [projection field] pushed over the color, and a green after-image was obtained for red and orange when the projection-screen was middle gray or black."[2] The writers were able to obtain after-images of the above colors under the conditions cited by Miss Fernald as most favorable, but instead of finding them to be the most favorable they found them to be almost the most unfavorable. As stated above, their most favorable conditions were black preëxposure, black campimeter screen, black projection field; and their most unfavorable conditions were white preëxposure, white

[1] Fernald, G. M., Psychol. Rev. Monog., 1909, X., pp. 37–45.

[2] *Op. cit.*, p. 82.

campimeter screen, and white projection field. The variation of the factors between these extremes gave the phenomenon with a frequency ranging between maximal and minimal. Working with the conditions she found to be most favorable, Miss Fernald was able to obtain the after-image in only approximately 31 per cent. of the total number of cases.[1] With the conditions we have found to be most favorable the after-image may be obtained in practically every case.

4. Miss Fernald's explanation of her results is also in contradiction to the facts as we find them. (*a*) She says that the most favorable conditions are gotten when the "projection-screens were determined so as most to emphasize the after-image color and the background least to favor the stimulus color."[2] The campimeter screen, then, that narrows the zone of sensitivity for a given color furnishes the most favorable conditions to be obtained for that color. The white screen is most favorable because "in so far as our results justify any conclusions concerning the color limit they seem to show that all the colors except the reds are perceived at a greater degree of eccentricity with the dark than with the light backgrounds. Red is seen as red to about the *same* degree of eccentricity with the dark and light backgrounds, but it is seen as yellow or orange with the dark background at the same points at which it is seen as colorless with the light background."[3] Her exception in case of red seems due to the fact that the limit for red is for her where first a trace of yellow comes in. If the limit for red had been taken at the point where the last trace of red is seen, as is usually done, red would have proved no exception to the other colors, and we could derive from her results the law that all the colors have a narrower limit with the white screen than with the dark or black screens. We do not find this to be true. For us blue and green have a wider limit with the black screen than with the white, and red and yellow a narrower limit. These results were obtained with the effect of preëxposure eliminated and with the illumination of the optics room carefully standardized by a method to be described in a later paper. Neither of these precautions was observed in Fernald's work. Their importance may be shown by the following results. As compared with the gray of the brightness of the color, a preëxposure of three seconds to black was found by one of the writers (Rand) to narrow the limits of sensitivity for red, green, and yellow 6°, and for blue 11°; a preëxposure to white to narrow the limits for red 5°, for green 2°, for yellow 4°, for blue 7°. At an eccentricity of 35° on the temporal meridian, a preëxposure of three seconds to black raised the limen for red 58°, for green 80°, for yellow 32°, and for blue 13°; a preëxposure to white raised the limen for red 45°, for green 55°, for yellow 12°, and for blue 7°. When the white campimeter screen was used, the changes in illumination from 11 A.M. until 4 P.M. on a bright day in September were found to vary the limits for the different colors from 4° to 6°. The change in the illumination of our optics room, lighted by skylight and provided with diffusion sashes to lessen the effect of external changes, from a bright morning to a cloudy afternoon was sufficient to vary the limits with a white screen from 6° to 14° for the different colors; and with a black screen from 2° to 7°. The greater variability is found for the white screen because the amount of contrast it induces is found to vary more with the change of illumination. (*b*) Miss Fernald seems to believe that the brightness process may have either a stimulating or an inhibiting effect on the color process. She says: "There seem to be two possible ways of explaining the action of brightness: Either the brightness of the stimulus has a direct inhibitory or stimulating

[1] Fernald, G., Psychol. Rev., 1908, XV., p. 33.

[2] Fernald, G., Psychol. Rev. Monog. Sup., 1909, X., p. 82.

[3] *Op. cit.*, p. 23.

effect on the color processes, or the brightness primarily affects the brightness substance, and the activity in brightness substance has some differential effect on the color activity. . . . The fact that our most striking effects were obtained when the brightness is superimposed on the color, *i. e.*, when the brightness is largely determined by contrast with a brightness background, or when the after-image is projected on a light or dark ground, seems at least to justify the statement that the superimposed brightness acts in such a way as to inhibit, increase, or modify the color activity."[1] Her claim that all the colors have their widest limits with the black screen and their narrowest with the white seems to indicate that she considers that white increases the color activity and that black decreases it. She says: "This brightness factor is effective to a very limited extent in central vision, to a much greater extent in peripheral vision. As we go out into the peripheral retina, the action of the white process is needed more and more, *i. e.*, the colors must be made lighter to be most strongly sensed."[2] Our results show that the brightness process, white, black, or gray, must be considered as always having an inhibitive action on the color processes. When the brightness process is added to the color process either as after-image or contrast, the amount of colored light coming to the eye remains unchanged and yet the saturation of the color is considerably decreased. Instead of being increased by the action of white and decreased by the action of black the saturation is decreased by the action of both, but much the most by the action of white for all colors for all parts of the retina with the exception of for red and yellow within a very narrow zone just within the limits of sensitivity. In this zone red and yellow have a higher limen in black than in white. It is not certain, however, that even in this zone black exerts the greater inhibitive action, for it is difficult to add the same amounts of black and white to red and yellow because these colors darken in the peripheral retina and it is hard to get a measure of how much black is added by this process alone. The relative amounts of inhibitive action by white, black, and gray of the brightness of the color can also be shown by the method of objective mixing. When equal amounts of white, black, and the gray are added in turn to a disc of color on the color mixer, the colored light coming to the eye is reduced an equal amount in each case, yet the apparent saturation of the color is very different on the three discs. It is much the greatest on the disc to which black has been added, next greatest on the disc to which gray has been added, and the least on the disc to which white has been added. Or to get a more exact measurement of the actions in each case, the color limen may be determined. An amount of color which is just noticeable when added to the black disc will give no color at all when added to the white or gray disc. A considerably larger amount must be added to the gray disc to give color, and a still larger amount must be added to the white disc than was added to the gray disc.

Such a confusion as Miss Fernald and many others before her have fallen into with regard to the relation of brightness to intensity or strength of color is apt to come from the failure to separate the action of the brightness or achromatic excitation from the action of physical intensity or energy of the light waves coming to the eye. When a colored light of low energy strikes the eye it is both unsaturated as to color and for the most of the colors of low brightness. As its energy is increased it becomes more strongly sensed as color and in most cases lighter. That the two changes go hand in hand when the physical energy of the colored light is changed, however, does not justify the inference that they will go hand in hand when there is no change in the energy

[1] *Op. cit.*, p. 79.
[2] *Op. cit.*, p. 73.

of the colored light—in other words does not justify the inference that an increase in the white excitation will heighten the color excitation. The central principle of Miss Fernald's method of working is to change the achromatic excitation without affecting the amount of colored light coming to the eye. In all such cases, with the possible exception of red and yellow for the small zone mentioned above, the saturation of the color decreases rapidly as the quality of the achromatic component is made lighter. In addition it is scarcely necessary to point out that just because a color reaches its maximal saturation at a given brightness as the energy of the colored light is increased, it does not follow that the achromatic excitation corresponding to this brightness is the most favorable in its action upon the color process. When the amount of colored light is rendered constant and the achromatic factor is varied, it is found that black is the most favorable quality of the achromatic series and the specific grays are favorable in proportion as they are near to black in quality. The gray of the brightness of yellow, for example, kills out the color in yellow when mixed with it almost as rapidly as does white and much more rapidly than does black and the darker grays. Thompson and Gordon, while in general agreeing with Fernald with regard to the effect of brightness relations, in one place seem both in addition and in contradiction to have fallen into this latter error. They say: "The effect of the background then seems to be this; that in a colored after-image, that color element is emphasized which in brightness approaches the brightness of the background [by background is meant here the field on which the after-image is projected], that is, on the lighter grounds the brighter element comes out and on the darker grounds the darker color element."[1]

By way of clearing the ground for explanation, the writers have made a detailed study of the influence of the various brightness qualities upon color in the central retina, and for a large number of meridians in the peripheral retina. Since a statement of the results obtained will be given in full in a later paper, nothing more than a general statement will be attempted here. In the central retina, white reduces the saturation of colors the most, the grays in the order from light to dark next, and black the least. In the peripheral retina, this law holds for blue and green out to the limit of sensitivity for all of the observers worked with; and also for red and yellow for all of the peripheral retina except a very narrow zone just within the limit of sensitivity. In this zone, black apparently inhibits red and yellow most strongly—at least, red and yellow have a higher limen here when mixed with black than when mixed with white or the grays. An ultimate statement of most favorable conditions for all parts of the retina, then, would have to take into consideration all of the facts. It would involve a more detailed consideration of the topography of the retina than can be gone into in this paper. In formulating our

[1] Thompson and Gordon, *op. cit.*, p. 128.

experimental technique, however, we have avoided, we believe, the difficulty raised by the exception to the law found just within the limit of sensitivity by employing inhibitive conditions sufficiently strong to allow us to work nearer the center of the retina, where the exception has never been found. Thus we have been able to use as our working principle the law that white inhibits the most, grays in the order from light to dark next, and black the least. But to determine in accord with the law even thus simply stated, the brightness quality of preëxposure, campimeter screen, and projection field that will give the conditions most unfavorable for the stimulus color and most favorable for the after-image color, is not easy. For example, in order to inhibit the stimulus color most strongly, the preëxposure must be black, so as to give a white after-image to fuse with the color. This effect could be strongly intensified by having the black preëxposure made through an opening in a white campimeter screen, and the color exposure, which comes immediately after and simultaneously with the after-image of the black preëxposure, made through a black screen. This would secure the greatest possible intensification of the white after-image, and, therefore, the greatest possible amount of inhibition of the stimulus color. In order to favor maximally the saturation of the after-image color, the after-image should be projected on a field of very dark gray or black.[1] As to campimeter screens to be used during the projection of the after-image, we have a choice again of brightness qualities ranging from white to black. White and the grays in proportion to their whiteness would intensify by contrast the blackness of the projection field, while black would exert little if any influence. The black screen, then, is probably the safest to use while the after-image is being observed for two reasons. (1) If one is working with a general illumination at all intensive, white and the grays in proportion to their whiteness induce enormously in the peripheral retina. This amount of induction of black carries the brightness quality beyond that

[1] It may be well to state that in our study of the effect of brightness upon color, the black used was the matt black of the Hering papers. When we state that black favors the saturation of colors, this black is referred to.

specified in our law as most favorable, namely, the blackness of the pigment of the Hering paper. (2) There is always danger that we may not be working far enough within the limit of sensitivity to escape the exception to our law of most favorable action. If, then, our formulation of conditions be correct, we should have a white campimeter screen during preëxposure to black, and a black screen during both the exposure of the stimulus color and the projection of the after-image. This would involve two changes of the card behind the stimulus opening in the screen, and one change of the screen. The change of cards causes no disturbance in our phenomenon, but a change of the campimeter screen in the interval between the preëxposure and the exposure to color would be fatal to the success of our experiments. This is because the white after-image would not last through the change, for reasons that have already been discussed; and the effect of the preëxposure on the stimulus color would therefore be lost. We are thus limited to one screen for a single experiment, and our problem becomes to determine which of the brightness qualities acting continuously through all three stages of the experiment will be the most favorable for our phenomenon. After rough preliminary tests, three screens were selected as representative of the action of all, namely, white, black, and a gray of the brightness of the color to be used. Of these three, the black screen was found to be much the most favorable. A consideration of the action of the three brightness qualities upon preexposure, stimulus color, and after-image shows sufficient reason for this. The effect of each is as follows: (1) The white screen intensifies the blackness of the preëxposure, darkens the stimulus card, and, in the peripheral retina, especially if the general illumination is intensive, piles up the blackness on the projection field to a degree that is unfavorable to the saturation of the after-image color. (2) The gray screen of the same brightness as the color adds blackness both to the preëxposure and to the projection field, but not so much as is added by the white screen. It has no effect on the stimulus card. (3) The black screen has no effect on the preëxposure; it induces white on the stimulus card and thus adds to the

effect of the preëxposure on the stimulus color; and it exerts little or no effect on the projection field. A comparison of these effects shows that the black screen in all probability inhibits the stimulus color more than any of the others, and is less unfavorable in its action upon the after-image color. For this reason, it gives the most favorable brightness conditions for obtaining our phenomenon. Considering all the factors, then, we find that apparently the most favorable combination that can be made for our purpose is black preëxposure, black campimeter screen, and black projection field. The results of our experiments show this to be true. Under these conditions, color was obtained in the after-image in practically every case. The next most favorable condition was given by the white or gray screen with black preëxposure and black projection field. The poorest results were obtained with a white preëxposure and white projection field. With this combination, color could not be gotten in the after-image with any consistency of result, whatever brightness quality was used in the campimeter screen.

Having thus worked our way through an explanation of our phenomenon and a determination of the conditions under which it can best be obtained, we will devote the remainder of the report of the work done by methods (*a*) and (*b*) to a brief review of the results obtained in support of the various points that have been made. Our general thesis was that the phenomenon under consideration is but a special case of the difference in the inhibitive action exerted upon color by the different brightness qualities. Color may be obtained in the after-image when none is sensed in the stimulus, if an unfavorable brightness quality is fused with the stimulus color and a favorable one with the after-image color. In detail, our first point was that for all parts of the retina and for all colors, with the exception of two over a narrow zone just within the limits of sensitivity, white reduces the saturation of color the most, the grays in the order from light to dark next, and black the least. This law was generalized from the results of fusion and limen experiments in a large number of meridians of the retina. Our second point was that the combination of the preëxposure and campimeter screen

most unfavorable to the saturation of the stimulus color was the most favorable condition for obtaining our phenomenon. The effect of preëxposure and campimeter screen upon the saturation of the stimulus color was measured in two ways: (1) by the effect on the limen color; and (2) by the effect on the limits of sensitivity.[1] Data were thus obtained which we could directly correlate with the frequency with which color was obtained in the after-image, and so determine whether our position was correctly taken. The results of this correlation show that, estimated in both these ways, the combination that proved the least favorable to the saturation of the stimulus gave color in the after-image in the largest percentage of cases; and, conversely, that the combination most favorable in its action on the stimulus gave color in the after-image in the smallest percentage of cases. A third point was that a black preëxposure and black screen gave the brightness conditions that were most unfavorable to the saturation of the stimulus color. An estimation of the effect of the different combinations of screen and preëxposure by either of the methods mentioned above brings out this point strongly. The least effect was found when preëxposure and screen were both of the brightness of the stimulus color. A fourth point was that preëxposure provides a stronger means of reducing the saturation of the stimulus color than does the screen. To make the test of this point absolute, the influence of one should be completely eliminated while the influence of the other is being determined. This can not be done. The eye must always have some preëxposure, and there will

[1] See Rand, G., 'The Factors Which Influence the Campimetrical Observation: A Quantitative Examination and Methods of Standardizing.' (In press.)

Of these two tests, the limen test has a much broader application, and measures much more directly what needs to be measured. It has a broader application because it can be made anywhere in the zone of sensitivity. It measures more directly what needs to be measured, because the results obtained show just how much color has to be present under a given condition to be sensed as color, while the results in the method of limits only express in terms of degrees how much the limit of sensitivity has been changed. This is a poor measure of how much the color in the stimulus has been inhibited under a given condition: because, in the first place, it is not a direct measure of this action; and, in the second place, the results obtained cannot be even roughly rendered into terms of direct measurement, owing to the fact that the sensitivity of the retina near the limits does not fall off either gradually or regularly.

always be a surrounding field. The effect of preëxposure, however, can be minimized by choosing it of the gray of the brightness of the color to be used as stimulus, and by making the stimulation to it extremely short. Working in this fashion, we have only a slight local brightness adaptation to modify the color excitation immediately following, the effect of which can be taken as practically negligible. The influence of the screen also can be minimized in a similar way, by having it always of the brightness of the color to be used as stimulus. Isolating the action of preëxposure and screen by this method, we estimated the effect of each in turn upon the saturation of the stimulus color, both by the effect on the limen of color and on the limits of sensitivity. Our results in both cases show that preëxposure can be made much the stronger factor. For example, the limits of sensitivity were never made to vary more than 4° by the most extreme changes that could be made in screens, while it could be varied as much as 14° by changes in the preëxposure. The difference stands out still more strongly in the effect on the limen, as would naturally be expected, since changes in the limen more directly express the differences in the inhibitive action than changes in the limits of sensitivity, as was shown in the footnote, p. 219. A fifth point was that black is the most favorable brightness quality for the projection field. This was shown very clearly by using projection fields of white, gray of the brightness of the stimulus color, and black, with each of the combinations of preëxposure and screen, and comparing the results obtained. In addition, these results, when compared with those obtained by varying the preëxposure and the campimeter screen, show that the brightness of the projection field is a very important factor—much more important than the brightness of the campimeter screen, and just as important, possibly more so than the brightness of the preëxposure.

Results in support of these points in general are given in Table I. In this table is shown the percentage of cases, based on twenty trials, in which color was obtained in the after-image when none was sensed in the stimulus. The object of the experiments was to determine the relative importance of the

three factors, preëxposure, campimeter screen, and projection field. The method of experimenting in the following cases was to keep two of the factors constant and find the effect of varying the third. However, in order to show most effectively the most favorable conditions in decreasing order, the results have been grouped as follows. If the individual, horizontal columns are compared, the effect of campimeter screen is shown. If groups of three are compared, the effect of preëxposure is seen. If compared in groups of nine, the effect of projection is seen.

From the table it will be seen that projection field and preëxposure are the most important factors. Of the preëxposures, black is seen to be the most important. Its effect is greater on green and blue than on red and yellow. This is because the inhibitive action of the white after-image following the preëxposure is greater for blue and green than for red and yellow. The full effect of preëxposure was not obtained in our experiments because with a given black preëxposure we did not work as near the center of the retina as we might have done.

In method (*c*) also (see p. 208), the vertical campimeter was used to give the stimulus. Black was chosen both for the campimeter screen and for the projection screen in each case. Otherwise the procedure was the same as for after-images in direct vision. The results obtained were also similar, with the exception that not so much decrease of illumination was needed to obscure the stimulus color, and more saturated after-images were obtained. The stimulus time in indirect vision must always be shorter than in direct vision. (From 2 to 3 seconds was used.) This is due to the rapid exhaustion to color in indirect vision. After-images fall off in saturation if exhaustion to the stimulus color is carried beyond the stationary-point.

2. *Contrast*

It was found that contrast could be induced for certain colors when the general illumination was sufficiently reduced to obscure the color in the inducing stimulus. Very strong

Table I

Showing the Percentage of Cases in which the Colored After-Image was Obtained when No Color was Sensed in the Stimulus, under All Variations of Screen, Preëxposure, and Projection Field

Campimeter Screen	Preëxposure	Projection	Red	Yellow	Green	Blue
Black	Black	Black	100	100	100	100
Gray	Black	Black	100	100	80	70
White	Black	Black	50	40	50	40
Black	Gray	Black	40	30	30	20
Gray	Gray	Black	50	30	0	0
White	Gray	Black	50	40	0	0
Black	White	Black	50	30	40	0
Gray	White	Black	45	20	0	0
White	White	Black	45	30	0	0
Black	Black	Gray	40	70	50	40
Gray	Black	Gray	20	40	20	20
White	Black	Gray	20	30	0	0
Black	Gray	Gray	0	0	0	0
Gray	Gray	Gray	0	0	0	0
White	Gray	Gray	0	0	0	0
Black	White	Gray	0	10	0	0
Gray	White	Gray	0	0	0	0
White	White	Gray	0	10	0	0
Black	Black	White	0	0	10	0
Gray	Black	White	0	0	0	0
White	Black	White	0	20	0	0
Black	Gray	White	0	0	0	0
Gray	Gray	White	0	0	0	0
White	Gray	White	0	0	0	0
Black	White	White	0	0	0	0
Gray	White	White	0	0	0	0
White	White	White	0	0	0	0

contrast was aroused under these conditions by standard red, dark orange, and yellow of the Hering series of colored papers.

Contrast discs were cut as follows. The inducing surface was made of two colored discs; one 25 cm., the other 10.5 cm. in diameter. The contrast surface was made by placing between these discs on the color-mixer a black and white disc, 11.5 cm. in diameter. When these were rotated, the black and white mixed to give a gray ring 1 cm. in width, separating the two colored surfaces. The proportions of black and white were taken so that the gray ring matched in brightness the

color used, the brightness of the color having been determined by means of Schenck's flicker photometer.

The observations were made in the dark-room described above. The color of the inducing surface was obscured by a decrease of the illumination. As in the after-image experiments, this was done by two methods, one in which the observation was made after the eye had adapted to the illumination chosen; the other before adaptation had set in. The latter method gave a much stronger effect, for although decrease of illumination within wide limits increases contrast effect in general, this increase is very much greater while the illumination is decreasing. That is, if two determinations of contrast are made for the same inducing and contrast surfaces, one in which the judgment is passed while the illumination is decreasing, the other after the eye has become adapted to the illumination at which the former judgment was made, it will be found that the former determination greatly exceeds the latter. Thus it appears that color induction is greatly enhanced while the retinal change corresponding to dark-adaptation is going on. This phenomenon will be treated more fully in a later paper on contrast. Our present purpose is satisfied with the consideration of the phenomenon at one point in the series of decreasing illumination; namely, the point at which the color in the inducing surface is obscured. This point varies greatly for the different colors used. It is the highest for red, next highest for yellow and dark orange, lowest for green, and next lowest for blue.

The amount of contrast induced in each case was determined by two methods. In each method a measuring-disc was used, compounded from discs of the proper colors and of black and white. In the first method, the comparison-judgment between the contrast ring and the measuring-disc was made at the illumination at which the inducing color was obscured. This method may not be clear to the reader. It may seem, for example, that a degree of illumination that wholly obscures the inducing color would also wholly obscure the color of the measuring-disc. This is not true because of the different effect of the decrease of illumination upon the saturation of the dif-

ferent colors, *i. e.*, blue, green, and blue-green, the colors used for the measuring-discs, retain considerable color at the illumination at which red, yellow, and dark orange, the inducing colors used, lose their saturation. The difficulty with the method is, that the measurements on the comparison-disc at a low illumination are not of standard value because of decrease of saturation, and thus convey little meaning to the mind of the reader. In order to get measurements in standard terms, a second method was resorted to, the results of which are more intelligible although the method of judgment is less accurate. In this method the comparison was made in terms of the saturation of colors on the measuring-disc at full illumination. Since one of the terms of comparison is a memory-image, a time error was involved in this method. This was to some extent compensated for, however, by working both ways, *i. e.*, a part of the judgments were made by first getting a memory-image of the contrast sensation at decreased illumination and comparing that with the measuring-disc at full illumination, and a part were made by the inverse procedure.

The tables recorded in the report are compiled from the results of Misses Chamberlain (*C*) and Rand (*R*), fellows in psychology, of Bryn Mawr College, and Bunker (*B*), graduate student.

3. *The Purkinje-Brücke Phenomenon*

The Purkinje-Brücke phenomenon was found by us to demonstrate in a very striking fashion that it is not necessary for the inducing excitation to condition sensation directly in order that color induction may take place.

This phenomenon was first described by Purkinje in 1825.[1] He says: "Man liege ein weisses Quadrätchen von der Breite zweier Linien auf einen schwarzen Grund, starre es 20–30 Secunden an, und blicke sodann ins Schwarze hinein, so wird man ein noch dunkleres Viereck sehen, dessen Randes mit einem graulichen, sich allmählich verlierenden Scheine umgeben sind. Lagt man auf den schwarzen Grund statt des weissen Quadrätchens ein rothes, so zeigt sein grünes Spectrum einen

[1] Purkinje, J., 'Beobachtungen und Versuche zur Physiologie die Sinne,' 1825, II., p. 107.

Table II

C. Showing the Amount of Contrast Induced when the Color in the Inducing Surface is Unsensed

Stimulus	Contrast Ring	Direct Judgment	Memory-image Judgment
Red.	White 41° Black 319°	Green 130° Black 230°	Green 171° Black 119° White 70°
Yellow.	White 236° Black 124°	Blue 151° Black 130° White 79°	Blue 76° Black 223° White 61°
Dark orange.	White 82° Black 278°	Green 210° Blue 56° Black 94°	Green 168° Blue 14° Black 172° White 6°

Table III

Observer *B*

Stimulus	Contrast Ring	Direct Judgment	Memory-image Judgment
Red.	White 41° Black 319°	Green 228° Black 132°	Green 214° Black 94° White 52°
Yellow.	White 236° Black 124°	Blue 121° Black 142° White 97°	Blue 163° Black 59° White 138°
Dark orange.	White 82° Black 278°	Green 136° Blue 118° Black 106°	Green 152° Blue 106° Black 102°

Table IV

Observer *R*

Stimulus	Contrast Ring	Direct Judgment	Memory-image Judgment
Red.	White 41° Black 319°	Green 225° Black 135°	Green 166° Black 126° White 68°
Yellow.	White 236° Black 124°	Blue 137° Black 189° White 34°	Blue 82° Black 159° White 119°
Dark orange.	White 82° Black 278°	Green 195° Blue 64° Black 52° White 49°	Green 127° Blue 44° Black 159° White 30°

rothlichen Schein; auf gleiche Weise das blaue Spectrum einen orangen Schein, u.s.w. Man sieht heraus dass die objective Farbe nicht bloss in die Tiefe der Retina, sondern auch in die Breite einwirkt jedoch nicht gleich mässig nach ihrer ganzen Ausbreitung, sondern zunächst an der Gränze der heterogenen Beleuchtungen am intensivesten."

The phenomenon with some modifications was next described by Brücke in 1851,[1] and by Aubert in 1862.[2] The color or added brightness in the after-image was called by Brücke an after-effect of induction;[3] by Aubert an after-image of contrast. Attention was again called to the phenomenon by Hering in

[1] Brücke (*Pogg. Ann.*, 1851, LXXXIV., pp. 418–448) says (p. 47): "Einen dritten Beweis endlich kaum man aus der Beobachtung der negativen Nachbilder entnehmen› welche nach diesem Versuchen zur Erscheinung kommen welche zeigen, dass die inducirten Farben als solche im Stande sind, complementären gefärbte Nachbilder hervorzurufen." His demonstration consists in getting the after-effect of looking towards the light through squares of red, green and violet glass with small discs of black paper placed at their centers. He describes the after-effect as follows: "Bei Anwendung des rothen Glases erscheint als negatives Nachbild eine helle rothe Scheibe auf dunkel grünem Grunde. Hierein liegt nichts Auffallendes und dieser Erfolg würde sich nach Analogie der Versuche von Fechner erklären lassen, auch ohne dass man eine Nachwirkung der inducirten Farbe voraussetze. Wende ich aber das grüne Glas an, so habe ich von der dunklen Scheibe ebenfalls ein helles rothes Nachbild und der Grund ist Schwarz, oder wenigstens so dunkel, dass ich seine Farbe nicht mit Sicherkeit habe unterscheiden können. Hier hat also das inducirte Grün Roth hervorgebracht. während das inducirende gleichzeitig kein deutlich gefärbtes Nachbild erzeugte, In derselben Weise zeigte sich mir bei Anwendung des violetten Glases das negative Nachbild als eine gelbgrüne Scheibe auf schwarzem Grunde." In two cases here Brücke apparently has the positive excitation induced across the black disc, and in two cases the negative excitation. But since he does not make induction apply to the negative excitation, as has been done later, he does not explain this case as after-image of contrast, but makes it instead analogous to the phenomenon described by Fechner.

[2] Aubert (*Pogg. Ann.*, 1862, CXVI., pp. 249–279) says on p. 259: "Ausserdem ist es aber auffallend dass der simultane Contrast selbst noch einen successiven Contrast hervorruft, indem die durch den simultanen Contrast complementär gefärbten weissen Quadrate noch einmal complementäre Nachbilder hervorrufen, so dass jene Quadrate im Nachbilde dieselbe Farbe, nur sehr bedeutend abgeschwächt haben wie der Grund." Aubert observed white squares on a colored ground. In the positive sensation the squares took on a tinge of color complementary to the background, and in the after-image of the same color as the background. That is, a white square on a red background appeared greenish in the stimulus and red in the after-image. He says: "Besonders schön und mit einem eigenthümlichen Glanze erschienen die Nachbilder der weissen Quadrate auf dem blauen Streifen."

[3] Brücke applies the term induction to the positive excitation only.

1878.[1] Hering worked with achromatic sensation alone. He also called the phenomenon an after-image of contrast sensation,[2] and upon his observations based his arguments against Helmholtz's theory of contrast. Continuing the discussion, the experiments were extended to color sensations by Ebbinghaus[3] who considered the phenomenon a combination both of after-image of contrast and of contrast induced by an after-image.

The following form of experiment was adapted by us from Ebbinghaus. Squares 20×20 cm. of red, green, blue, and yellow Hering papers were fastened upon neutral gray backgrounds. Passing vertically through the center of these squares, gray strips 2×20 cm. of Hering papers numbers 8, 24, 2, 41, respectively, were pasted. The after-effect of stimulation by this combination is a square of a color complementary to the color of the stimulus square, traversed by a strip of the same color as the stimulus square. The red square, for example, gives a green square traversed by a strongly saturated

[1] Hering, E., 'Zur Lehre vom Lichtsinn,' Wien, 1878, pp. 5–18.

[2] On pp. 5–18 Hering describes experimental conditions similar to those described by Purkinje. Here he calls the phenomenon successive light induction. On pp. 24–29 he describes slightly different experimental conditions. Two dark gray strips of the same brightness, 3 to 4 cm. long and .5 cm. broad, are fastened parallel to each other 2 cm. apart, one upon a white and the other upon a black ground. A fixation-point is taken on the boundary between the white and black backgrounds midway between the strips. By contrast the strip on the white ground looks darker than the strip on the black ground. When an after-image of the strips, the one lightened, the other darkened by contrast, is obtained, their brightness values are reversed, and a still greater brightness difference between them is found. This difference toward black on one hand, and toward white on the other, Hering calls an after-image effect of the brightness contrast induced in the stimulus. The phenomena obtained by these two sets of conditions are in every sense identical. One can scarcely see a reason for the separate treatment they have received by Hering.

[3] Ebbinghaus (*Grundzüge der Psychologie*, Erster Band, p. 239) says: "Man lege zwei mässig grosse Blätter z. B. von sattgrüner Farbe so auf einen grauen Grund, dass nur ein schmaler, etwa 5 mm. breiter horizontaler Streifen zwischen ihnen freibleibt, und lasse diesen von einer unbefangenen Person eine Weile fixieren. Dann lasse man sie das Nachbild auf einem etwas unregelmässig geformten Grunde entwerfen, z. B. auf dem Fensterkreus, und frage, was sie sehe. Man wird so gut wie ausnahmlos die Antwort erhalten: 'einem grünen Streifen.' Der objektiv völlig neutrale Streifen hat durch die zweimalige Kontrastwirkung (im Vor- und Nachbilde), die sich von einer ausgedehnten Umgebung auf seine schmale Fläche konzentriert, eine so intensive Färbung bekommen, dass er sofort die Aufmerksamkeit auf sich zieht, während die röthliche Nachbildfärbung seiner Nachbarschaft bei den Unregelmässigkeiten der reagierenden Fläche in der Regel gar nicht beachtet wird."

red strip; the green square, a red square traversed by a green strip. Now if the color of the strip is an after-effect of a previously induced contrast, we have a strongly saturated, long-enduring after-image of an unsensed stimulus, for the brightness opposition of the gray strip to the inducing color, and the rather intensive illumination under which we worked, both combined to inhibit all contrast color in the stimulus. At this stage of the work we do not feel prepared to take positive ground on the question of explanation, but have the following evidence to offer that the Brücke interpretation is correct.

i. Evidence that the Color in the Strip is an After-Image of a Previous Contrast Sensation, rather than Contrast in the After-Image

(*a*) In the after-effect, the strip and square apparently develop, fluctuate, and die away independently of each other; the strip frequently develops before the square, especially if the stimulation has been very short; it invariably lasts longer than the square, returning several times after the square has finally disappeared; and in fluctuating, the two figures behave much as two after-images are observed to do, so far removed from each other as to be wholly without the sphere of reciprocal influence. The strip is frequently present when the square has disappeared, and vice versa. It rarely happens that their phases coincide, and when they do, the connection is obviously a chance one.

Records on this and the following points were taken from a number of observers, both experienced and inexperienced. The results given in the following tables are typical. The work was done in a large optics room, lighted on one side by a bank of windows extending nearly to the ceiling. The observer, head in rest, was seated in front of these windows so that the light coming from above and either side fell uniformly upon the projection-field of engine-gray cardboard, 1 meter distant. The time of stimulation, unless otherwise stated, was 30 seconds, and the unit of record was one second. The recording apparatus used throughout consisted of a Ludwig-Baltzar kymograph; a double electro-magnetic recorder, and two con-

tact keys, one for strip and one for square; a Jacquet chronograph set to seconds; and a lamp rheostat to reduce the current from the lighting circuit.

Table V

C. Showing the Independent Phases of Visibility and Invisibility of Square and Strip

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Red, 20×20 cm....	8	5	6.2	56	7.1	57	113
Gray No. 8, 2×20..	15	6	5	89.5	4	60	149.5
Green, 20×20	2	6	5	15	3.8	7.5	22.5
Gray No. 24, 2×20.	6	7	4.6	32	3.7	22	54
Yellow, 20×20.....	3	17	8	32	11	33	65
Gray No. 41, 2×20.	8	18	6.4	58	2.4	19	77
Blue, 20×20.......	4	12	6.5	32.5	5	20	52.5
Gray No. 2, 2×20..	9	11	6.1	61	3.7	33	94

Table VI

Observer *B*

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Red, 20×20 cm....	11	12	8.5	102	4	44.5	146.5
Gray No. 8, 2×20..	18	9.5	4.2	79	4	72	151
Green, 20×20......	4	5	3.1	15.5	4.1	16.5	32
Gray No. 24, 2×20.	6	7	4.4	30.5	3.8	22.5	53
Yellow, 20×20.....	3	3.5	3.1	12.5	7.5	22.5	35
Gray No. 41, 2×20.	7	3	3.1	25	3.3	23	48
Blue, 20×20.......	6	13	4.1	28.5	7.3	44	72.5
Gray No. 2, 2×20..	11	3	3.6	43	3.3	36	79

Table VII

Observer *R*

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Red, 20×20 cm....	3	5	4.8	19	10.6	32	51
Gray No. 8, 2×20..	7	5	3.5	28	3.3	23	51
Green, 20×20......	3	2	6.2	25	4	12	37
Gray No. 14, 2×20.	5	7	5.3	32	3.6	18	50
Yellow, 20×20.....	2	12	7.7	23	9.5	19	42
Gray No. 41, 2×20.	7	13	5.5	44	2.3	16	60
Blue, 20×20.......	3	22	9.8	39	4.3	13	52
Gray No. 2, 2×20..	10	7	4.2	46	3.1	31	77

(*b*) The mutual independence of strip and square can be further indicated by a method of concomitant variations. That is, the strip can be made to fluctuate less and last longer without any corresponding change in the fluctuation and duration of the square. And conversely, the square, or rather what in this variation corresponds to it, can be made to change its duration and rate of fluctuation, without any corresponding change in the fluctuation and duration of the strip. Both of these variations are based upon the effect of the arrangement relative to the direction of greatest involuntary eye-movement, upon the fluctuation and duration of a strip after-image. If the observer has more eye-movement in the horizontal than in the vertical, a strip after-image with its greater dimension in the vertical will fluctuate more and last a shorter time than one of the inverse arrangement. It may be stated as a law[1] that whenever the direction of greatest eye-movement is along the shorter dimension of the after-image, the maximal fluctuation and minimal duration is attained for that form of after-image.

Thus, to vary the duration and rate of fluctuation of the strip without changing them in the square, we need only to arrange the stimulus so that the longer dimension of the strip is first in the vertical and then in the horizontal. This rotation of the stimulus 90° will obviously have no effect upon the duration and rate of fluctuation of the after-image of the square, since both of its dimensions are equal. If we wish to make the converse variation, *i. e.*, change the duration and rate of fluctuation of the outer figure without changing them for the inner, we shall obviously have to make the outer figure a strip and the inner a small square. Then by rotating the stimulus 90° we shall increase or decrease the duration and rate of fluctuation of the outer figure, depending upon whether its shorter dimension is in the vertical or horizontal, while the duration and rate of fluctuation for the inner figure will not be affected.

(*c*) The Brücke interpretation seems also to receive negative support from the following fact. When one observes the

[1] Ferree, C. E., 'Intermittence of Minimal Visual Sensations,' *Amer. Journ. of Psychol.*, 1908, XIX., pp. 101–103. For explanation of this phenomenon see same reference, pp. 126–127.

Table VIII

C. Showing by Method of Concomitant Variations a Decrease in Fluctuation and an Increase in Duration of the Strip with no Significant Change in the Phases of the Square

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Blue, 20×20 cm.	3	25	15.3	61	5.7	17	78
Gray No. 2, 2×20 (vertical)	11	12	6.8	81	3.3	36	117
Blue, 20×20.......	2	48	20.6	62	5.8	11.5	73.5
Gray No. 2, 2×20 (horizontal)	9	11	9.4	94	4.3	39	133

Table IX

Observer *B*

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Blue, 20×20	7	6	6.2	50	3.9	27	77
Gray No. 2, 2×20 (vertical)	13	4	4.1	57	2.2	29	86
Blue, 20×20	10	13	4.4	48	2.4	24	72
Gray No. 2, 2×20 (horizontal)	9	5	7	70	2.9	26	96

Table X

Observer *R*

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Blue, 20×20	3	17	7.5	30	5	15	45
Gray No. 2, 2×20 (vertical)	7	7	4.4	35	2.1	15	50
Blue, 20×20	3	14	7.8	31	3.5	14	45
Gray No. 2, 2×20 (horizontal)	3	14	10.5	42	3.3	10	52

Table XI

C. Showing by Method of Concomitant Variations a Decrease in Fluctuation and an Increase in the Duration of the Square with no Significant Change in the Phases of Strip

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Blue, 20×.5 (vertical)	9	9	4.3	43	1.5	14	57
Gray No. 2, .5×.5 .	0	9	9	9			9
Blue, 20×.5 (horizontal)	5	15	9.7	58	2.4	12	70
Gray No. 2, .5×.5 .	0	7	7	7			7

TABLE XII

OBSERVER *B*

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Blue, 20×.5 (vertical)	8	6	3.3	30	2.3	18	48
Gray No. 2, .5×.5	0	7	7	7			7
Blue, 20×.5	4	10	9	45	2.5	10	55
Gray No. 2, .5×.5	0	8	8	8			8

TABLE XIII

OBSERVER *R*

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Blue, 20×.5	7	5.5	4	32	2	14	46
Gray No. 2, .5×.5	0	5	5	5			5
Blue, 20×.5 (horizontal)	3	43	17	68	1	3	71
Gray No. 2, .5×.5	0	10	10	10			10

stimulus through tissue-paper or under decreased illumination, the relative duration of strip to square in the after-effect is very greatly increased. This should not take place if a color in the strip after-image is induced by the color in the after-image square. The ratio should remain constant or approximately so, *i. e.*, since the intensity of the after-image square has been reduced by weakening the color of the stimulus square by tissue paper, a corresponding weakening would be expected in the color induced in the strip. The observation thus seems to furnish a negative indication that the after-image interpretation is correct. Relative to this observation, however, two points need to be taken into account. (1) An inspection of the tables shows that although there is an increase in the ratio of duration of strip to square, there is an actual decrease in the absolute duration of the strip. This might be supposed to indicate a tendency for the strip to vary with the square and thus to favor the contrast interpretation; but the increase of relative duration is too great for this to be probable. Besides, the decrease in absolute duration can be readily accounted for from the other side by a decreased retinal induction in the

stimulus due to the decreased saturation of the square. (2) The second point is quite aside from differential evidence as between the Brücke and Ebbinghaus interpretations. When the stimulus was observed through tissue-paper or under decreased illumination, considerable contrast color developed in the stimulus, where before there had been none, yet the after-image was less than in the former case. This seems to indicate the following. (*a*) The contrast sensation is only an equivocal index of the amount of excitation set up on the retina by a neighboring surface. This excitation may under one set of conditions arouse an intensive sensation, and under other conditions be equally strong, at least as far as after-effect goes, and excite no sensation. (*b*) Brightness opposition inhibits only the contrast sensation. It apparently does not inhibit the corresponding retinal induction due to the neighboring surface, at least not its power to give after-effects. That is, the brightness opposition between the square and strip in the stimulus was greater when the tissue-paper was not used and yet the strongest after-image of the contrast excitation was obtained in this case. These suggestions are thrown out merely tentatively and are meant to apply only within the bounds of the evidence offered.

Since the results are similar for both the tissue-paper device and the decrease of illumination, tables will be given only for the former.

TABLE XIV

C. SHOWING THE PHASES OF INVISIBILITY AND VISIBILITY OF STRIP AND SQUARE AND THEIR RELATIVE DURATIONS, OBSERVED UNDER TISSUE PAPER

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Red, 20×20	0	3	3	3			3
Gray No. 8, 2×20 ..	3	4	2.5	10	3	9	19
Green, 20×20	0	7	7	7			7
Gray No. 24, 2×20.	2	5	3.3	10	6.5	13	23
Yellow, 20×20	1	8	4.8	9.5	3	3	12.5
Gray No. 41, 2×20.	4	8	3.8	19	3.6	14.5	33.5
Blue, 20×20	1	5	6	12	6	6	18
Gray No. 2, 2×20 .	4	3	2.3	14	2.5	10	24

Table XV

Observer *B*

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Red, 20×20	0	2	2	2			2
Gray No. 8, 2×20	3	1	1.9	7.5	4.8	14.5	22
Green, 20×20	0	7	7	7			7
Gray No. 14, 2×20	2	4	4	12	5.8	11.5	23.5
Yellow, 20×20	0	4.5	4.5	4.5			4.5
Gray No. 41, 2×20	3	4	3.1	12.5	4	12	24.5
Blue, 20×20	1	3	2.5	5	7	7	12
Gray No. 2, 2×20	7	4	3.5	28	3.1	22	50

Table XVI

Observer *R*

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Red, 20×20	0	3	3	3			3
Gray No. 8, 2×20	3	3	2	8	3.3	10	18
Green, 20×20	0	8	8	8			8
Gray No. 14, 2×20	3	4	3.5	14	3.3	10	24
Yellow, 20×20	1	6	4.5	9	2	2	11
Gray No. 41, 2×20	3	5	4.5	18	4	12	30
Blue, 20×20	1	5	4	8	5	5	13
Gray No. 32, 2×20	4	5	4.6	23	3	12	35

ii. But if a Contrast Effect, Evidence that it May Take Place when the Inducing Color is Unsensed

As already stated, the strip frequently develops before the square; it invariably lasts longer than the square; returning several times after the square has finally disappeared; and in fluctuating its phases rarely coincide with those of the square, *i. e.*, it is frequently visible when the square is invisible, and conversely.

Thus it is immaterial for our thesis which interpretation be given to the phenomenon. For (*a*) if the after-color in the strip be a contrast sensation, our results show that it may be set up when the inducing excitation is not directly conditioning sensation; and (*b*) if it be an after-image sensation, they show that it may be aroused by a previous excitation which did not itself directly give rise to sensation.

FIG. 1. (Observer *R.*) Records showing the fluctuations and duration of strip and square.

III. Explanation

A later paper will contain a history of the observations on the effect of brightness changes, general and local, upon color phenomena, beginning with Purkinje.[1] Purkinje's observations cover the following points. (1) The relative difference in the brightness values of the spectral colors at full and decreased illumination. (2) The difference in the effect of change in brightness upon the saturation of colors. (3) The changes in color-tone produced by changes in brightness.

After-Image

The explanation of the possibility of getting color as an after-image from a stimulus in which no color can be sensed rests in general with the second point of Purkinje's observations; namely, the difference in the effect of change in the brightness of different colors upon their saturation. In every case in which a colored after-image was obtained from a colorless stimulus, it was gotten at a degree of brightness which worked against color saturation in the stimulus and relatively favored it in the after-image. Take, for example, the case of central vision. By the first method the influence of the brightness factor was introduced by means of a decrease in the general illumination. Yellow and red and orange lose their saturation at an illumination that permits of a supraliminal saturation of blue and green. The case, then, is simple. There was retinal excitation in the cases of red, yellow, and orange, but it was obscured for sensation by the brightness factor. The after-effect of this excitation, however, was not obscured for sensation. It was relatively favored, and, therefore, gave the after-images which were observed. There is nothing new or strange in principle about this phenomenon. The foregoing results show that it depends entirely upon the effect of the brightness changes in a color upon its saturation. These effects were observed and reported as far back as the time of Purkinje, and have been discussed sporadically in the literature from that time to this. By the second method the unfavorable

[1] Purkinje, 'Beobachtungen und Versuche zur Physiologie der Sinne,' 1823, I., p. 109.

brightness quality was added to the stimulus color by objective mixing, contrast, or after-image; and the favorable brightness quality was added to the after-image by means of the projection field. The after-image method was found to be the most effective for adding the unfavorable brightness quality to the colored stimulus because by means of it (*a*) the amount of colored light coming to the eye is not reduced as it is by the method of objective mixing; and (*b*) the unfavorable brightness quality added to the stimulus color is not added to the after-image color also, as is done under the conditions of the experiment by the method of contrast.

For the after-image in peripheral vision, we have a slightly different case. The peripheral retina differs from the central with regard to the effect of change in brightness upon both the saturation and the quality of colors. With regard to saturation, we have in general merely an exaggeration of the condition found in the central retina, *i. e.*, brightness changes produce greater difference in effect in the case of the different colors. With regard to color tone, the change is not in the same direction in every case as it is in central vision, *i. e.*, in central vision at full illumination. In this paper, however, we are concerned with the effects upon saturation alone. Moreover, under a given set of conditions more of the brightness quality can be added as after-image and contrast in this region of the peripheral retina than in the central retina because of the increased sensitivity of the former to achromatic after-image and contrast. We have then in these regards especially favorable conditions in the peripheral retina for obscuring stimulus color by brightness changes, and for relatively favoring the development of the after-image. We have as an additional factor the enhanced sensitivity of the peripheral retina to adaptation and after-image effects. It adapts very rapidly to color stimuli and responds quickly with a vivid after-image of short almost momentary duration, often described as a vivid flash of color. All of these factors make it comparatively easy to get after-images of unsensed stimuli in peripheral vision, the only fact relative to our problem that needs to be explained.

Contrast

It was found to be especially easy to arouse green, blue-green, and blue as contrast sensations when their inducing stimuli do not directly excite a sensation of color. Two factors are involved in this result. (1) A decrease of the illumination obscures red, orange, and yellow before it obscures their contrast colors, green, blue-green, and blue. Hence, induction and the effect of decrease of illumination upon it aside, there is reason in the nature of the color processes themselves why red, for example, should not be sensed when its contrast color, green, is sensed. But (2), in addition to this, decrease of illumination enormously enhances the induction of the contrast color, this effect being greater for green, blue, and blue-green than for their complementary colors red, yellow, and orange.

The Purkinje-Brücke Phenomenon

Until a final decision has been made between the after-image and the contrast interpretations, the Purkinje-Brücke phenomenon presents a two-fold problem. From the side of the after-image interpretation it must be explained how an after-effect so intensive and of such long duration can be obtained from a stimulus of so little apparent intensity; *e. g.*, in our form of the experiment, no color at all could be sensed in the strip. From the side of the contrast interpretation, it must be shown how contrast color can be gotten in the after-effect of the strip when the square is not in sensation; *i. e.*, before the square appears, in the invisibility phase of its intermittence, and after its final disappearance.

At this stage of the work, an explanation will not be attempted. From the Brücke side, however, it may be pointed out that evidence has already been given that color in the contrast sensation is only an equivocal index of the actual amount of the corresponding retinal color excitation. Also, that, while this induced excitation may arouse a strong sensation, a weak sensation, or even none at all, depending upon concomitant brightness conditions, contour, etc., nevertheless, in all of these cases, it gives rise to after-sensations of color, and to the most intensive in the cases we used, when no color was sensed in the

stimulus. In fact, it was just to take advantage of this point that our method was devised. We introduced brightness opposition between strip and inducing color to prevent the induced excitation from arousing a sensation of color, knowing that its power to condition color in the after-image was not diminished thereby, providing the brightness conditions were favorable for the development of the color. The brightness conditions were made tolerably favorable by choosing a shade of gray for the stimulus strip whose after-image was approximately the brightness of the after-image color. From the side of the Ebbinghaus interpretation, the writers have not at present even a plausible suggestion to offer in explanation. However, lack of explanation of this phenomenon does not limit its confirmation of our thesis that stimuli in which no color is sensed may arouse after-image and contrast sensations in which color is sensed.

We wish to state in conclusion that our chief interest in the problem has been its share in the broader problem presented by the Purkinje observations. We do not think that sufficient attention has been given to the second and third of these observations and the light they may throw on color theory. Up to this time, theory has practically ignored the effect of brightness changes upon the saturation and quality of color sensation. These effects seem to argue a functional connection between chromatic and achromatic processes which should not be disregarded.

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AN OPTICS-ROOM AND A METHOD OF STANDARDIZING ITS ILLUMINATION

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I. INTRODUCTION

In a previous article[1] the statement was made by the writers that all comparative estimates of the sensitivity of the retina to color (limens or limits) should be made in daylight instead of in the dark-room. This is to eliminate the influence of the field surrounding the colored stimulus, and of the preëxposure. When the surrounding field is black, white is induced by contrast across the stimulus color. Since the colors all differ in brightness,[2] the induction takes place in different amounts for the different colors. This white, in proportion to its amount, reduces the action of the colors on the retina. Further, a given amount of white affects to different degrees the action of the different colors on the retina. To eliminate this twofold unequal action, the surrounding field should be made in each case of the brightness of the color to be used. This can be done by working in a light-room of constant intensity of illumination and by making the surrounding field of a gray paper of the brightness of the stimulus color. In order to accomplish this and at the same time be able to work in any meridian of the retina we choose, we have constructed a special piece of apparatus which we call a rotary campimeter.[3] The influence of preëxposure is even more important than of sur-

[1] Ferree and Rand, 'A Note on the Determination of the Retina's Sensitivity to Colored Light in Terms of Radiometric Units,' *Amer. Journ. of Psychol.*, 1912, XXIII., p. 331.

[2] In a later paper, one of the writers (Rand) will show that it is of no advantage to equate in brightness in determining the limits of color sensitivity, and that harm results in so many ways from the attempt to equate, that it is doubtful whether it should be done even in determining the limens of color in the more sensitive parts of the retina.

[3] See C. E. Ferree, 'Description of a Rotary Campimeter,' *Amer. Journ. of Psychol.*, 1912, XXIII., pp. 449–453.

rounding field. If the preëxposure is to black, white is added as after-image to the stimulus color. The effect of a black preëxposure upon the stimulus color is greater than the effect of a black surrounding field because more white is added as after-image of preëxposure than is induced by contrast from the surrounding field. This effect also can be eliminated only by working in a light-room of constant intensity of illumination and choosing as preëxposure a gray of the brightness of the color to be used.

Standardization for either one of these factors, however, can be accomplished for one degree of illumination only.[1] As the general illumination changes, the relation of the brightness of the preëxposure and of the surrounding field to the brightness of the colored stimulus changes. It is obvious, then, that if standardization is to be accomplished with regard to the influence of either of these factors, some means must be devised of maintaining the general illumination of the retina constant. No satisfactory method has as yet been obtained for keeping the illumination of a room by daylight constant. To keep it constant presupposes what has not as yet been provided, namely, a sensitive means of measurement. Constancy may be approximated by artificial illumination, but no artificial source of light has yet been devised which gives a light that approaches average daylight[2] sufficiently closely in composition to warrant its use in color work. Of the various sources of light the Moore Tube comes nearest to doing this, but spectrophotometric and colorimetric determinations show that the light from it contains an excess of blue,[3] and, therefore, although it

[1] When the colored light used to stimulate the retina is independent of the general illumination, *e. g.*, when it is obtained from the spectrum, from monochromatic sources, or from standard filters, these two factors alone will modify the result of the color observation. If, however, light reflected from a pigment surface be used as stimulus, a change in the illumination will in addition change the amount of colored light coming to the eye.

[2] For results of measurements of the color values of average daylight, see Nichols, E. L., *Transactions of the Illuminating Engineering Society*, 1908, III., p. 301. Ives, H. E., 'The Daylight Efficiency of Artificial Illuminants,' *The Illuminating Engineer*, 1909, IV., pp. 434–442; and 'Color Measurements of Illuminants,' *Transactions of the Illuminating Engineering Society*, 1910, V., pp. 189–207.

[3] See Ives, H. E., 'Color Measurements of Illuminants,' *Transactions of the Illuminating Engineering Society*, 1910, V., p. 206; and Rosa, E. B. quoted by Moore,

has been adopted by various textile concerns for use in color matching, its substitution for daylight can scarcely be recommended for the more exact requirements of color optics. Ives and Luckiesh[1] attack the problem of producing artificial daylight from another side. By their subtraction method they claim to have gotten the closest approximation to average daylight yet attained. They aim to cut out by absorbing screens the excess of red and yellow in artificial light due to the comparatively low temperature of artificial illuminants. Tungsten lamps are used by them as the source of light, and two kinds of commercial glass approximating in their absorptive action cobalt blue and signal green are used as screens. In order to correct for the pronounced band of yellow-green transmitted by the cobalt blue, a film of gelatine dyed with rozazeine is also used. Although according to comparative measurements made by Ives and Luckiesh the light thus gotten is the closest approximation to average daylight yet obtained, still it shows a deficiency of 15 per cent. in the green and about 25 per cent. in the blue. Moreover the spectrum of this light does not show the brightness distribution of the spectrum by daylight. Since the absorbing screens cut down the light emitted by the tungsten lamp to 15 per cent. of its original intensity, the spectrum of the light finally given out shows the brightness distribution characteristic of lights of low intensity. We seem thus compelled either to give up the investigation of the color sensitivity of the retina for daylight illumination, or to devise some means of keeping this illumination constant. At an early stage of our work of standardizing the factors extraneous to the source of light, we were compelled to take into account the influence of the changes in the illumination of the visual field upon the color observation. The changes of illumination that took place from day to day, the progressive changes during the day, and the many sudden changes even in the course of an hour, rendered any constancy, or close reproduction of results entirely out of the question.

D. McF., 'A Standard for Color Values,' *Transactions of the Illuminating Engineering Society*, 1910, IV., p. 224.

[1] Ives, H. E., and Luckiesh, M., 'Subtractive Production of Artificial Daylight,' *Electrical World*, 1911, LVII., pp. 1092–1094.

In order to obtain a standard illumination, two things are necessary: (*a*) A means of controlling the illumination must be provided, which is sufficiently sensitive to cause small changes. (*b*) A method of measuring the illumination produced has to be devised; at least, a means must be secured for determining when an illumination has been obtained that is equal to a given preceding illumination. It is the purpose of this paper to describe an optics-room provided with means of control which we have found adequate to meet the above requirements; and to state a method of identifying and reproducing any given illumination of this room.

II. Description of Optics-Room

The dimensions of the room are 12½ × 10 ft. It is situated on the upper floor of an isolated building and is lighted by a skylight 8 × 7½ ft. Beneath the skylight two diffusion sashes, 4 × 7½ ft., are swung on hinges so that they can be raised or lowered as desired. The framework of these sashes is made of light-weight iron. For convenience of local control of illumination, if needed, each sash is divided into four units by means of cross-pieces. The sashes are filled with double-strength glass ground on one side, so adjusted to the frame that they can be removed easily for cleaning or for the substitution of some other kind of glass in case that is desired. This glass diffuses the light so effectively that local shadows cast by the cross-pieces in the framework of the skylight are completely eliminated, while the sudden changes of illumination produced by the passage of the sun behind a cloud are reduced to a minimum. This diffusion seems to have the further advantage of reducing the yellowness of direct sunlight below the limen of sensation. At least, when working under the sash, the observer never judged a gray exposed through the campimeter opening as yellow under any local conditions, as frequently happened when working under direct sunlight.

The room is planned also so that small changes of illumination can be produced, ranging from the intensive illumination of a south-exposure skylight to the blackness of a moderately good dark-room. Two provisions are made for this. (1) The

diffusion-sashes are made so that any or all of the panes of ground glass can be quickly and easily taken from the sash, and anything can be substituted that is desired; or the illumination can be varied by placing layers of tissue paper above the glass. (2) The room is provided with two curtains mounted on heavy spring rollers. One is a white curtain made of thin muslin; the other is a black light-proof curtain so mounted that, when drawn, its edges are deeply enclosed in light-proof boxing extending along the four walls of the room. One or both of these curtains can be drawn any distance that is desired, and the illumination can thus be changed gradually from a very intensive brightness to a fairly good blackness. To aid in getting dark-room effects, the doors of the room are carefully boxed and curtained. One requirement of a perfect dark-room, however, is lacking, namely, the walls and floor of the room are painted white. This is because it is of advantage in the light-room work, and because complete blackness is not needed in the type of work for which the room is devised.

III. Method of Standardizing

As stated earlier in our paper, no satisfactory means of determining the amount of daylight illumination in a room has been provided by the physicist, so there is little hope at this time of solving the problem from that side. The brightness induction of the peripheral retina, however, has been found by us to be extremely sensitive to changes in the general illumination. This phenomenon seems to provide us with a sensitive measure of these changes while, at the same time, it represents the combined effects for sensation of the principal subjective factors that might vary from day to day.[1] To apply the method in its most sensitive form, the inductive power of white was chosen because it is the most strongly affected by illumination changes. For example, when No. 14 Hering gray was used as stimulus and white as campimeter screen, a noticeable change was produced in the induction when the white curtain of the optics-room was pulled forward 1 cm.[2]

[1] This means of identifying the illumination of a room was devised by Rand.

[2] The sensitivity of this method of detecting changes in the general illumination was compared with the sensitivity of the Sharpe-Millar portable photometer. In

from a position in which its edge was directly above the long axis of the campimeter. This caused a change in the illumination of the room so small that it could not be directly sensed. Further, at 11 o'clock in the morning of a bright day in September, when a point at 25° on the nasal meridian was stimulated, one of the writers (Rand) reported that the white screen induced black across the stimulus No. 14 gray to an amount that caused it to equal in brightness 107° of black and 253° of No. 14 gray; at 2 o'clock of the same day the induction was increased until the No. 14 gray matched 150° of black and 210° of the gray; at 4 o'clock of the same day the No. 14 gray matched 180° of black and 180° of the gray.[1] Working at 25° in the temporal meridian, this observer reported at different times during one day and on different days, the wide variations shown by the following figures: 283° of black, 225°, 145°, 190°, 238°, etc. Another observer (Miss Campbell) reported less induction, but her variations from time to time were equally great. At 25° in the temporal meridian, she found at different

this photometer one of the comparison fields is illuminated by the light of the room and the other by a standard tungsten lamp enclosed in the photometer box. When the room is illuminated by daylight, the field receiving the light of the room is seen as white while the field lighted by the tungsten lamp appears as a saturated orange. The difference in color between the two fields renders the photometric judgment difficult and makes the instrument very insensitive for daylight tests. For example, our tests showed that by the method for identifying an illumination described in the text, a change in illumination could be detected which was produced by drawing the white curtain 1 cm. from a position in which its edge was directly above the long axis of the campimeter. But with the receiving surface of the portable photometer in precisely the same position as the stimulus screen of the campimeter, the edge of the curtain had to be moved 11.3 cm. in order that the change of illumination might be detected. Moreover, this amount of change could be detected only in case the photometric field was continuously observed while the curtain was being drawn, in which case the comparison field was observed to be slightly darkened. The judgment was made, then, in terms of a just noticeably different brightness of the field which was illuminated by the daylight, rather than in terms of a disturbance in the brightness-equality of the two fields. When, on the other hand, the judgment was made in terms of a just noticeable disturbance in the equality of the two fields, as the judgment would have to be made if the photometer were to be employed for the reproduction of any former illumination taken as standard, the curtain had to be drawn 44.2 cm. before the change could be detected. This j. n. d. represents an amount of illumination equal to 2.5 foot-candles.

[1] This increase in the inductive action of the screen caused by the decrease in illumination, was accompanied by a shrinkage of the zones sensitive to color covering an area of 4° to 6°.

times 80° of black, 103°, 160°, 175°, etc. After a careful study of the phenomenon with different screens and with different backgrounds, the inductive action of the white screen upon a stimulus of No. 14 Hering gray, at 25° in the temporal meridian, was found to provide the best means of detecting changes in the illumination of the optics-room. At this point on the retina, the induction was by no means minimal, nor was it sufficiently great to cause the medium gray chosen for our stimulus to appear too dark to give a small j. n. d. of sensation. Having thus provided ourselves with a means of producing small changes of illumination and a method of detecting them, we had in order to complete our work but to choose an illumination for each observer, which could be used as standard. Since we wished to work on both light days and days of medium darkness, an average had to be chosen as our standard from the measurements obtained on a number of days ranging from light to dark, so that on bright days, the room could be darkened, and on dark days it could be lightened until this value was obtained. For observer *A* (Rand) an illumination was selected which caused an induction of black across no. 14 gray stimulus viewed at 25° in the temporal meridian to an amount which caused the gray stimulus to equal in brightness 210° of black and 150° of no. 14 gray; for observer *B* (Ferree) 180° of black and 180° of no. 14 gray; and for observer *C* (Campbell) 145° of black and 215° of no. 14 gray. The amount of black induction was identified in each case by means of a measuring-disc made up of sectors of black paper and no. 14 gray of the Hering series. This measuring-disc was carried by a motor and placed just behind the 25° point. The observer fixated the 25° point and compared the gray of the measuring-disc as seen in central vision with the gray of the stimulus seen 25° from the fovea. The sectors of the measuring-disc were then changed until the two grays were of equal brightness.

Previous to each series of observations the illumination of the room was changed until the amount of brightness induction was brought to the value chosen as standard. It was tested at intervals during the sitting and was readjusted when

necessary. Details of the method of doing this are as follows. When the white screen and the no. 14 gray stimulus had been put in place, the observer took his position and adjusted the fixation-knot in front of the motor for the 25° point on the temporal meridian. The measuring-disc set at the standard value was mounted on the motor. The observer reported whether the stimulus appeared lighter or darker than the measuring-disc, or of a brightness equal to it. If the judgment lighter or darker was given, the curtain was drawn one way, or the other until the stimulus accurately matched the measuring-disc in brightness.

This method not only gives a sensitive measure of the changes of illumination of the visual field and a successful means of standardizing the illumination of a room by daylight, but it has in addition advantages for work in psychological optics not possessed by an objective standardization, could that be successfully obtained. The problem of standardization includes more for the psychologist than it does for the physicist, for the former has variables to take into account in addition to the changes that may take place in the energy of the stimulus. Even though the illumination of the room be made objectively constant, we should expect variations in the response of the retina to this illumination because of its own changes from time to time. Brightness contrast, for example, might be expected to vary from sitting to sitting even when the stimulus conditions are kept absolutely constant. Two factors would be concerned in these variations: changes in the inducing power of the surrounding parts of the retina, and changes in the sensitivity of the local area. These changes would take place even when the usual precautions known to the experimenter in this field have been observed. Such precautions are commonly limited to fatigue, adaptation, etc. These precautions do not provide for the changes that occur in the retina from day to day. Moreover, they do not adequately guard against the variations to which they are intended to apply, for no precaution can adequately guard against a change in a factor, unless some measure of that factor be had. So far as the writers know, in these general

precautions intended to keep the state of the retina constant, no measure of the variable factor has been provided to test the adequacy of the method. The method proposed by us, however, is planned with this in view. It takes into account not only the objective, but the subjective variables, and reduces both to a constant. For example, when no. 14 gray surrounded by the white field is made equal to the measuring-disc composed of 210° of black and 150° of the no. 14 gray for observer *A*, it means that the observation may be begun with the assurance that the total result of all the factors—the illumination of the room, the local sensitivity of the retina, and the inductive action of the surrounding parts of the retina —is the same as in the preceding observation.

What has just been said should not be considered as more than a general statement of the application of the principles of the method. In actual practice a greater refinement of working may be attained. If, for example, one wishes to use a preëxposure differing in brightness from that of the colored stimulus, and doubts whether a test which covers only the local sensitivity of the retina and the inductive action of the surrounding parts is a sufficient check upon the after-image sensitivity, he may make his standard include the effect of the preëxposure he wishes to use. In short, if he does not consider adequate the more general test we have described, he may duplicate, in establishing his standard, any combination of brightness factors, due to preëxposure, brightness of screen, or what not, that he may wish to use in his experiment proper.

The test of a method is how well it works. The test of this method is that we shall be able closely to duplicate our results from sitting to sitting regardless of the changes in the outside illumination from day to day or from morning until afternoon. The method stands the test. Long series of observations in the peripheral retina show a very small M.V. —much less even than is shown in the ordinary color observations in the central retina, where, as compared with the peripheral retina, the factors extraneous to the stimulus exert little influence.

The following table has been compiled from a number of observations to show the variations in the results of color limens and color limits (*a*) when the general illumination was controlled according to the method described above, and (*b*) when no more precautions were observed than were used by previous investigators. In previous investigations of the color sensitivity of the peripheral retina, care has been taken to work only at the same hours of days that appeared equally bright, or, if on days of different brightness, to make a rough approximation of preceding illumination by means of curtains without using either a definite standard or means of measuring. For our work with the illumination controlled, the gray of the brightness of the color at the illumination selected as standard was used for the preëxposure and the campimeter screen. For the work without especial control of the illumination, the gray of the brightness of the color for one of the days selected as typical was used throughout for preëxposure and screen. This gave in the first case complete elimination of the effect of preëxposure and surrounding field, and in the second case elimination as complete as could be gotten without accurate control of the general illumination. Results are given in the table for blue and green only because the sensitivity to these colors is affected most by changes of illumination.

Stimulus	Illumination	Screen and Preëxposure	Variations of Limits on Different Days	Variation of Limens on Different Days
Green.....	Controlled.........	Gray No. 9	0°	0°[1]
	Uncontrolled......	Gray No. 8	4°–6°	60°–82°
Blue......	Controlled.........	Gray No. 33	0°	2°–3°[2]
	Uncontrolled......	Gray No. 32	4°–5°	18°–30°

[1] The limen for green was taken in both cases at 25° on the temporal retina.
[2] The limen for blue was taken in both cases at 40° on the temporal retina.

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THE EFFECT OF CHANGES IN THE GENERAL ILLUMINATION OF THE RETINA UPON ITS SENSITIVITY TO COLOR[1]

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I. Introduction

It is the purpose of this paper to show the effect of changes in the intensity of the illumination of the field of vision upon the results of investigations which deal with the sensitivity of the retina to color.[2]

A method of standardizing the illumination of the field of vision was described in an earlier paper.[3]

II. Historical

The effect of the general illumination of the retina on color

[1] From the Bryn Mawr Psychological Laboratory.

[2] With regard to this effect two cases may be recognized: (1) When the colored light used to stimulate the retina is independent of the general illumination, *e. g.*, when it is obtained from the spectrum, from monochromatic sources, or from standard filters; and (2) when it is obtained by reflection from pigment surfaces. In the first case the effect is exerted in the following ways: (*a*) by changing the brightness relation of the preëxposure to the colored surface, (*b*) by changing the brightness relation of the surrounding field to the colored stimulus, (*c*) by altering the sensitivity of the retina to brightness after-image and contrast and thus changing the effect of the brightness of the preëxposure and of the surrounding field upon the sensitivity of the retina to the colored stimulus. To these effects is added in the second case a change in the amount of colored light coming to the eye.

[3] Ferree and Rand, 'An Optics-room and a Method of Standardizing its Illumination,' PSYCHOL. REV., 1912, XIX., pp. 364–373.

sensitivity has been recognized since the time of Purkinje and Aubert. It has been studied in some detail by a number of experimenters, among whom may be mentioned Kramer and Wolffberg. Both have shown that the sensation aroused by the colored stimulus is weakened by a reduction of the general illumination but neither has given a method of keeping the general illumination constant. Kramer's[1] purpose was to determine the sensitivity of the eye under different intensities of daylight and artificial illumination. His method was as follows. Stimuli, 4 mm. square, of blue, yellow, red, and green paper on a black background were used. The distance at which the stimulus had to be placed from the observer to be just recognized as colored was tested by sunlight and when the sky was obscured by clouds and for three intensities of each of the following sources of artificial illumination: candle-light, gas, petroleum, sodium, potassium, strontium, and calcium lights. His results show the following facts: (1) Red is seen at the greatest distance in all lights except calcium, in which case green is seen when placed farther away than red. The other colors are recognized in the order green, yellow, blue. (2) All the colors are recognized at a greater distance when seen by sunlight than when illumined by artificial light or the dull light from a clouded sky. (3) As the intensity of the artificial illumination is decreased, the colors must be placed nearer the eye to be recognized. In drawing his conclusions with regard to comparative sensitivity, Kramer ignored the white contrast which the black background induced across the stimuli. The induction across stimuli whose sizes were only 4 mm. square must have been considerable. It was, moreover, of different amounts in each case; because brightness contrast is greatest when there is maximal brightness opposition. The modification of the light colors, as a result of contrast induction, must, therefore, have been greater than that of the dark colors. Wolffberg's[2] interest was in the influence of gradual alterations of the general illumination on

[1] Kramer, J., 'Untersuchungen über die Abhängigkeit der Farbenempfindung von der Art und dem Grade der Beleuchtung,' Inaug.-Diss., Marburg, 1882.

[2] Wolffberg, 'Ueber die Prüfung des Lichtsinnes,' *A. f. O.*, 1887, XXXI., pp. 1–78.

the light and the color sensitivity of the central and of the peripheral retina. His room was illuminated by daylight entering through a window. Fifteen different degrees of illumination were produced by fastening from one to fifteen thicknesses of tissue-paper over the window. The illumination obtained when the window was uncovered was called 15/15; when covered with one thickness of tissue-paper, 14/15, etc. His method of determining the effect of variations of illumination upon the central retina was as follows: Pigment stimuli were placed at a standard distance of 5 meters from the observer, and the size of stimulus necessary to render it just visible in its true color was determined. In the peripheral retina, he investigated to what extent the limits of white and of colored stimuli were altered by reducing the illumination. In all his experiments, the stimuli were fastened on a black background. Wolffberg's results for the central retina are shown in the following table. The stimuli were circular in shape and of diameters given in columns 2, 3, 4, 5, and 6.

Illumination	Size of Red Stimulus	Size of Blue	Size of Green	Size of Yellow	Size of White
15/15	.5 mm.	3 mm.	3 mm.	1.5 mm.	.2 mm.
14/15	1.5	5	4	2	.5
13/15	2	6	6	4	1
12/15	2.5	12	12	4.5	2
11/15	3	20	20	5	2.5
....	....	....	....	....	....
5/15	10	50	50	10	6

These results show that in the central retina a decrease of illumination has greater effect upon the sensation of color than upon the sensation of white. Wolffberg next tested the effect of a gradual decrease of illumination upon the limits of sensitivity to white and to the colors. He found that the extent of the visual field was not narrowed for white when the illumination was decreased to 1/15. The color limits, however, narrowed gradually when the illumination was decreased from 15/15 to 3/15. The narrowing was in no case more than 15°. The relative extents of the fields remained unaltered, *i. e.*, the order of size was in every case blue, red, and green.

Although special investigations have been conducted by Kramer, Wolffberg, and others to show the effect of changes in the general illumination upon color sensitivity, in general little if any precautions have been taken by earlier experimenters to prevent such changes when investigating color sensitivity. Either the experimenter has not considered the influence of the general illumination, or he has been satisfied to take the rough precaution to work only on bright days at stated hours. Ole Bull,[1] for example, commented at length on the factor of general illumination, but suggested no method for its standardization. He writes: "The amount and nature of the general illumination are of more significance in perimetrical observations than one is accustomed to consider. It must always be noted whether the sky is clear or cloudy, whether it rains or snows. The extreme limits of the visual field for mixed light undergo such wide fluctuations that it is of little value to establish an average limit on the basis of a number of measurements. Changing illumination, conditioned by the time of day and of year during which the work is carried on, as well as the locality in which it is undertaken, produce variations in the same stimulus large enough to cause differences of from 10° to 20° [in the limit of sensitivity]. Especially in the nasal parts of the retina does the illumination influence the color limits, while their position remains more constant in the temporal retina." Fernald,[2] however, did make some attempt to obtain a standard illumination. She arranged white curtains at the windows of her optics-room, which could be lowered on bright days and drawn on dark days. This rather crude method was used also by Thompson and Gordon.[3] It is scarcely necessary to point out that the method lacks the first essential of standardization, namely, a means of measuring.

It is surprising that Wolffberg, as the logical corollary of his work, did not draw attention to the importance of standard-

[1] Ole Bull, 'Perimetrie,' Bonn, 1895, p. 8.

[2] Fernald, G. M., 'The Effect of the Brightness of Background on the Extent of the Color Fields and on the Color Tone in Peripheral Retina,' Psychol. Rev., 1905, XII., p. 392.

[3] Thompson and Gordon, 'A Study of After-images on the Peripheral Retina,' Psychol. Rev., 1907, XIV., p. 122.

izing the illumination of the visual field in all work on the color sensitivity of the retina, and show how it could be accomplished by a modification of his method of working. He already had at hand one of the essentials for standardizing, namely, a method of changing the illumination of his room. The other essential, a method of measurement by means of which an illumination could be identified with a previous illumination chosen as standard, might have been derived from his results. For example, it would seem to have been a simple matter for him to have chosen as standard the particular illumination at which the red stimulus of 2.5 mm. diameter, the blue and green of 12 mm. each, the yellow of 4.5 mm., and the white of 2 mm. were just recognizable at a distance of 5 m. Stimuli of these sizes, it will be seen from the tables, were just recognizable at this distance at the illumination called 12/15, when 15/15 represents the illumination "bei günstige Tagesbeleuchtung." Using this condition as an index of the standard illumination, he could at any time have adjusted the illumination of the room by adding to or subtracting from the layers of tissue-paper covering the window, until the stimuli of these sizes were again just recognizable at the given distance. The accuracy and sensitivity of this method could have been tested by comparing the results of a series of determinations. An accurate and highly sensitive method sustaining some similarity in principle to the method suggested here is described in another paper in this volume of the Review.[1]

III. Experimental

The effect of change of illumination was forced upon our attention early in the investigation of the factors that influence the color sensitivity of the retina. For example, in preliminary work done by the writer on a well-lighted porch on Long Island, changes in color-tone were observed, when certain colors were compared in the central and in the peripheral retina, that are not found at all under the more intensive illumination of our optics-room when neither of the curtains is

[1] See footnote 2, p. 1.

drawn; and the peripheral limits of color were narrower by 5° to 12°. Furthermore, on a dark day, it was found that the limits of stimuli exposed through an opening in a white screen were reduced by about 4° as compared with the limits taken on a bright day. The change was less considerable with black and gray screens. The change in color-tone was most conspicuous in case of green.[1] On dark days, the green stimulus appeared as a pale unsaturated blue before becoming colorless in passing from the center to the periphery of the retina. This zone of blue was from 7° to 23° wide, in different meridians of the retina, with both white and black screens, but was wider with the black than with the white screen. On a sunny day, on the other hand, with the white screen green passed into bluish-green, then directly into gray, except in case of the upper regions where it appeared blue throughout a zone of about 4° in width. With the black screen, the blue zone was found only in the upper and temporal regions of the retina. The transition of green to yellow in the periphery that is generally reported in the literature was found in these experiments only when the gray screen was used. Yellow showed a color change that varied in amount with the degree of the general illumination. On a bright day with the white screen, it appeared reddish-orange. On a cloudy day, it was seen in the extreme periphery as a dark saturated red.

Working in our optics-room we found also that results taken on one day could not at all be duplicated on the following day. When the work was carried on under the most favorable conditions without special means of controlling illumination, namely, on bright days only, differences of 5° or more were found when the white screen was used. This necessitated a long series of observations if legitimate averages were to be obtained. Such a procedure is at best a poor makeshift and is besides of great disadvantage in many problems that come up in the work on color sensitivity. Particular instances of this may be found in investigations in which it is required to work in the region lying just within the limits of sensitivity, and in work on the after-images of stimuli in which no color is sensed.

[1] The green of the Hering series was used.

In the latter case the experiment requires that the stimulus be exposed just outside the limits of sensitivity determined with a given brightness condition, and that the observer should not be aware of the nature of the stimulus. In order to fulfill these requirements the experimenter must know the limits obtaining with a given brightness condition. It would be impossible to know this when the brightness conditions were subjected to the influence of changing illumination unless re-determinations were made at the beginning of each sitting and even frequently during its course. This would consume a great deal of time and would, besides, only roughly fulfill the requirements of the problem. A further and still more important example of the disadvantage may be found in the task we had set ourselves, namely, to investigate from point to point the sensitivity of the retina to each of the principal colors for three backgrounds in at least sixteen different meridians. In this work it is obvious that unless a standard illumination were provided, all comparative work would have to be done at one sitting. This is impossible. When time is taken between observations to guard against fatigue, at least three hours is required merely to outline the limits of sensitivity for a given color with one background for only one half of the retina. Even for this length of time there is no guarantee that the illumination has not altered. Thus at the outset of any extended investigation of color sensitivity, it is evident that, without a standard illumination, results will be of little comparative value.

In order better to know our factor and the ways in which it operates, a systematic investigation of the influence of changes of general illumination was carried on in our optics-room which is especially constructed to secure fine changes in illumination.[1] The experimentation was conducted by means of a rotary campimeter, described in full by Ferree, in the July number of the *American Journal of Psychology*.[2] Three observers acted as subjects. Since the results of all three are

[1] A description of this optics-room was given in the Psychological Review, September number, 1912, pp. 367–368.

[2] Ferree, C. E., 'Description of a Rotary Campimeter,' *Amer. Journ. of Psychol.*, 1912, XXIII., pp. 449–453.

similar in their general bearing on the problem, space will be taken for the results of two of them only, *A* and *C*.

Rough preliminary experiments showed that the primary effect of decreasing the illumination was an increase in the amount of contrast induced across the stimulus by the campimeter screen. With the white screen, the increased induction was the most pronounced and was sufficient to cause large changes in the limits and in the color-tone of the stimulus. In order to investigate this effect in detail, gradual changes of illumination covering a wide range were made by means of the curtains with which our optics-room is furnished. Attention was given to the following points. (1) A quantitative estimate was made of the influence of change of illumination upon the brightness induction of the campimeter screen. (2) The effect of this induction upon the limits of color sensitivity was determined. (3) The limens of the colors were measured at different degrees of excentricity at different illuminations. And (4) the influence of change of illumination upon the effect of the preëxposure on the limens and limits of color was investigated. The degrees of illumination chosen for comparison were the standard illumination, the method of obtaining which was described in an earlier paper,[1] and a decreased illumination which was similar to that obtaining on a cloudy afternoon. Measured in foot-candles by means of the Sharpe-Millar portable photometer, the standard illumination equalled 390 foot-candles, the decreased 1.65 foot-candles.

1. Quantitative Estimate of the Influence of Change of Illumination upon the Induction of Brightness by the Surrounding Field

The purpose of this investigation was to find out (1) how much the induction from white and black screens[2] is affected by a change in the general illumination; and (2) how much induction is gotten at decreased illumination from the gray screen which matches the color at standard illumination. The

[1] Ferree and Rand, *op. cit.*

[2] White and black screens are chosen because they represent the extreme cases of the effect of change of illumination.

induction in this latter case is caused by the change in the brightness relation between color and screens with decrease of illumination.[1] The campimeter screens served as inducing surface, grays of the brightness of the four principal colors of the Hering series both at standard and decreased illumination were used in turn as stimuli, and the amount of induction was estimated upon a measuring-disc, made up of adjustable sectors of the gray of the stimulus and white or black, according to the screen used. The measuring-disc was mounted on a motor which could be moved along the graded arm of the campimeter to any position from 20° to 92°. The gray stimulus was exposed through the opening of the screen in the usual manner. Two preliminary precautions were observed. (*a*) Since the brightness of the gray stimulus plus the induction of the screen was to be estimated by means of the measuring-disc, and since the brightness-value of the stimulus and of the disc changes with the amount of light that falls upon them, it was necessary to make sure before each measurement that the same amount of light fell upon each. This precaution was all the more necessary because the stimulus had to be placed behind the screen and the measuring-disc in front. In a given position of the apparatus, one or the other was apt to be shaded. The determination was made as follows: Measuring-disc, campimeter screen, and gray stimulus were all given the same brightness-value according to determinations made under conditions about which no doubt of the equality of the illumination of each could be entertained. Each was then placed in position for the experiment, and the position of the campimeter as a whole and of its various parts was adjusted until stimulus, screen, and measuring-disc were exactly matched in brightness-value. When an exact match was obtained we were guaranteed

[1] This latter determination is made to show that it is impossible to standardize the brightness of the surrounding field against the sudden and progressive changes of daylight that occur during the course of a single series of observations. These changes alter the brightness relation between the colored stimulus and the gray used as screen; therefore a match made at the beginning of a series will not hold throughout its course. For the same reason and to an equal degree the brightness relation between preëxposure and colored stimulus changes with change of illumination. It is, therefore, equally impossible to standardize the brightness of the preëxposure without some means of securing a standard illumination.

that all three were again equally illuminated. (*b*) The question arose whether brightness induction comes to its maximal value at once in the peripheral retina. A determination of the intensity curve of the contrast sensation was accordingly made at various points in the peripheral retina. It showed that contrast increases strongly for the first few seconds of stimulation. For this reason it was found to be necessary to make the judgment concerning the amount of induction of the screen, just as long after the induction had commenced as was done in the experiments to determine color sensitivity. In the color experiments an interval has to be allowed before the stimulus is exposed during which the observer obtains a steady fixation. During this interval of preëxposure, the eye is being stimulated by the campimeter screen and by the card which covers the stimulus. To prevent the preëxposure card from giving a brightness after-image which would fuse with and modify the stimulus, it should be chosen of a gray of the brightness of the color. In the same way, an interval has to be given in which to secure steady fixation when the amount of brightness induction is being measured. In order, then, to have the judgments made in each case the same length of time after induction had begun, it was necessary only to make the intervals of preëxposure of equal duration and to require that the judgments of each kind be made directly at the end of the preëxposure. In the case of the color experiments, the signal for the making of the judgment is the withdrawal of the preëxposure card and the exposure of the stimulus. For the judgments of induction, however, in which case the stimulus was the gray of the brightness of the color, it is obvious that no preëxposure card was needed, for preëxposure and stimulus were required by the conditions of the experiment to be the same. In this case, a word-signal had to be given to indicate the termination of the preëxposure interval and the instant at which the judgment was to be made.

Results when White and Black Screens were Used.—Observing these precautions as to the equality of the illumination of stimulus, screen, and measuring-disc, and as to the length of time the induction had had in which to increase before the

judgment was made, measurements were taken of the induction by white and black screens across grays of the brightness of the four principal colors at the illumination used. These measurements were made at various points of excentricity on the retina and for both standard and decreased illumination. The determination of the equality point between the stimulus and the measuring-disc was made as follows: The size of the white or black sector of the latter was changed until a preliminary judgment of equality was made. Then the j. n. d. on either side of this point was determined both by ascending and by descending series and an average of the results was taken as the final value of the induction. Measurements were taken at 25° and 40° on the temporal meridian, and at 55° and 70° on the nasal. The conditions at the nasal 55° point were very similar to those at 25° on the temporal side. The measurements at 70° nasal were midway in value between those at 25° and 40° on the temporal. The 40° point is very near the limits of color sensitivity in this meridian, and the induction here is very great. For one observer, the darker stimuli appeared black at this point, when the white background was used. In such cases, the difference between the induction at standard and at decreased illumination is more clearly shown by the observations made at 25° temporal meridian and at 55° and 70° nasal meridian than at 40° temporal. We have, however, chosen for two reasons to present in the following table only the results obtained in the temporal meridian. (1) The results obtained in this meridian demonstrate sufficiently well all the facts that need be taken into consideration. Space will not, therefore, be given to the results for both meridians. (2) The second point of our problem requires us to correlate the increased amount of induction caused by a given decrease of illumination with the change in the color limits it produces. The limits of color sensitivity can be more easily investigated in the temporal meridian because the sensitivity to some colors extends in the nasal region beyond the 92° point, which is the limit of measurement for the apparatus we used. This is true in particular in case of observer *C* as may be seen in Table XI. Both purposes of the investigation are, then,

better satisfied by results obtained in the temporal meridian.

The results show in general the following facts.

1. The amount of induction from the white screen is greater than that from the black screen.

2. The amount of induction increases with the distance from the fovea.

3. The amount of induction increases with decrease of illumination.[1]

4. The amount of increase under decreased illumination is greater in case of the white screen than in case of the black screen.

5. The white and black screens induce more contrast across the stimuli that are farthest removed from them in brightness, and least across those which are most like them. That is, the white screen induces more black across the gray of the brightness of blue than across a gray of the brightness of yellow; and the black screen induces more white across the gray of the brightness of yellow than across a gray of the brightness of blue.

Results are given in detail in Tables I. and II. Table I. gives the results for observer *A* taken on the temporal meridian, and Table II., the results for observer *C* for the same meridian. There is some difference in the amount of induction reported by the different observers, but since the preceding general statement of results is clearly borne out in every case, it is not deemed necessary to give space to results from all the observers used. In these tables, column 1 gives the degree of excentricity at which the observation was made; columns 2, 3, and 4 show respectively the stimulus used, and the amounts of induction from the white and the black screens at standard illumination. Columns 5, 6, and 7 give the same data for decreased illumination.

Results when the Gray Screen Matching the Colored Stimulus in Brightness at Standard Illumination is Used.—It was neces-

[1] This statement is meant to apply only to the range of illumination worked with. The induction was not measured when the illumination was very low, nor when it was very intensive.

Table I

A. Showing the Amount of Contrast Induced by the White and the Black Screens at Standard and Decreased Illumination upon the Grays of the Brightnesses of the Colored Stimuli at Standard and Decreased Illumination[1]

Fixation	Standard Illumination			Decreased Illumination		
	Stimulus (Gray of Brightness of Each of the Four Colors at Standard Illumination)	Amt. Induction of White Screen	Amt. Induction of Black Screen	Stimulus (Gray of Brightness of Each of the Four Colors at Decreased Illumination)	Amt. Induction of White Screen	Amt. Induction of Black Screen
25°	gray No. 2	Black 135°	White 110°	gray No. 2	Black 220°	White 170°
	gray No. 8	Black 155°	White 60°	gray No. 6	Black 270°	White 80°
	gray No. 24	Black 230°	White 28°	gray No. 41	Black 323°	White 40°
	gray No. 32	Black 290°	White 12°	gray No. 20	Black 330°	White 30°
40°	gray No. 2	Black 200°	White 300°	gray No. 3	Black 320°	White 360°
	gray No. 8	Black 300°	White 132°	gray No. 5	Black 360°	White 180°
	gray No. 24	Black 0°	White 60°	gray No. 50	Black 360°[2]	White 0°[3]
	gray No. 29	Black 360°	White 28°	gray No. 13	Black 360°	White 100°

[1] It is obvious that the method of expressing the amount of brightness induction used in this and the following tables gives an underestimation. Suppose, as is shown in Table I., that No. 24 Hering gray has been darkened by induction until it matches in brightness a disc made up of 230° of black and 130° of the No. 24 gray. The amount of induction is greater than is represented by the 230° of black because the induction has not lessened the amount of light coming to the eye from the grey paper while the addition of 230° of black to the measuring-disc has cut off approximately 2/3 of the light coming from the gray paper. That is, in the one case enough black has been added by induction to reduce 360° of No. 24 gray to the given point in the brightness scale, while in the other enough black was added by direct mixing to lower only 130° of No. 24 gray to this point in the scale. Moreover, the underestimation will be increased by this method of measuring in proportion as the amount of induction is increased because the greater the induction is the more black and the less gray will have to be used in the measuring-disc. All that can be said accurately is that a certain gray darkened or lightened by induction matches in brightness a gray made up of a certain amount of the given gray plus a certain amount of black or white. The exact amount of the induction can not be separated out. Further, just because the brightness added by contrast does not alter the amount of light coming to the eye while the brightness added in any method of measurement does change this amount of light, the writer knows of no way by which an exact expression can be attained. The

Table II

Observer *C*

Fixation	Standard Illumination			Decreased Illumination		
	Stimulus (Gray of Brightness of Each of the Four Colors at Standard Illumination)	Amt. Induction of White Screen	Amt. Induction of Black Screen	Stimulus (Gray of Brightness of Each of the Four Colors at Decreased Illumination)	Amt. Induction of White Screen	Amt. Induction of Black Screen
25°	gray No. 2	Black 70°	White 55°	gray No. 2	Black 130°	White 70°
	gray No. 8	Black 84°	White 48°	gray No. 6	Black 155°	White 59°
	gray No. 24	Black 93°	White 30°	gray No. 40	Black 187°	White 45°
	gray No. 32	Black 160°	White 15°	gray No. 17	Black 244°	White 22°
40°	gray No. 2	Black 110°	White 200°	gray No. 3	Black 216°	White 340°
	gray No. 7	Black 142°	White 160°	gray No. 4	Black 230°	White 320°
	gray No. 24	Black 180°	White 95°	gray No. 50	Black 360°[4]	White 0°[5]
	gray No. 27	Black 214°	White 35°	gray No. 7	Black 300°	White 108°

method she has used, however, does serve as a means of comparing the amounts of induction occurring under different conditions sufficiently accurately for her purpose at this point.

[2] The gray No. 50 was in reality rendered blacker by the inductive action of gray No. 24 than the Hering black we used on the measuring-disc. A match thus could not be attained with black 360° as the table indicates.

[3] There was no brightness induction in this case because the stimulus, gray No. 50, matches in brightness the black paper which formed the campimeter screen.

[4] See footnote 2 above.

[5] See footnote 3 above.

sary to perform the experiments bearing on this point at decreased illumination only. For them the campimeter screens which matched in brightness the four principal colors of the Hering series at standard illumination served as inducing surfaces. For the contrast surfaces, grays of the brightness of these colors at decreased illumination were chosen. The methods of measuring, precautions in working, parts of the retina investigated, etc., were the same as in the preceding determinations. The following general statement of results may be made. (1) At the 25° point the brightness of yellow was found not to have changed at all with the decrease of illumination produced by changing the illumination from the value selected as standard to the value selected for the comparison; the brightness of green lightened by an amount equal to the difference between No. 8 and No. 6 of the Hering series of grays; red darkened by an amount equal to the difference between No. 24 and No. 40; and blue lightened by an amount equal to the difference between No. 32 and No. 20. The amount of induction by the gray screen of the original brightness of the color upon the gray stimulus of the brightness of the color as altered by the decreased illumination, expressed in terms of Hering white and black, was for yellow 0°, for green 60° of white, for red 27° of black, and for blue 20° of white. (2) At the 40° point, the yellow darkened by an amount equal to the difference between No. 2 and No. 3 of the Hering grays; green lightened by an amount equal to the difference between No. 8 and No. 5; red darkened by an amount equal to the difference between No. 28 and No. 50; and blue lightened by an amount equal to the difference between No. 28 and No. 13. The amount of induction produced by these changes was for yellow 280° of black, for green 130° of white, for red 360° of black, and for blue 60° of white. These results are shown in detail in Table III.

2. The Effect of These Amounts of Induction Upon the Limits of Color Sensitivity

In order to obtain an estimate of the range of effect upon the limits of color sensitivity of the induction of the screens

Table III

A. Showing the Amount of Contrast Induced at Decreased Illumination on Grays of the Brightness of the Colors at Decreased Illumination by the Gray Screens Matching the Colors in Brightness at Standard Illumination

Fixation	Stimulus	Screen	Amount of Induction
25°	gray No. 2	gray No. 2	0°
	gray No. 6	gray No. 8	white 60°
	gray No. 41	gray No. 24	black 27°
	gray No. 20	gray No. 32	white 20°
40°	gray No. 3	gray No. 2	black 280°
	grgy No. 5	gray No. 8	white 130°
	gray No. 50	gray No. 24	black 360°[1]
	gray No. 13	gray No. 28	white 60°

at standard and at decreased illumination, the breadth of the color zones was determined at both illuminations (1) when white and black served in turn as campimeter screens; and (2) when a gray matching the color in brightness at standard illumination was used. The preëxposure was in each case to a gray of the same brightness as the stimulus at the illumination used. The point at which the color lost all trace of its original quality was recorded as the limit of sensitivity.

Results when White and Black Screens Were Used.—When the stimulus color is gotten by reflection from a pigment surface, two factors operate to give a change of result when the illumination is decreased. (1) There is a decrease in the amount of colored light coming to the eye. (2) There is an increase in the inductive action of the screen due to the change in the brightness relation of stimulus to screen and to the increased sensitivity of the eye to brightness contrast at decreased illumination.

In order to find out how much of our results with the white and black screens should be attributed to the decrease in the amount of colored light coming to the eye produced by the decreased illumination, and how much to the increased inductive action of the screens, the limits of sensitivity were also determined at both illuminations with the screens of the gray into

[1] The gray No. 50 was in reality rendered blacker by the inductive action of gray No. 24 than the Hering black we used on the measuring-disc. A match thus could not be attained with black 360° as the table indicates.

which the color disappears in the peripheral retina. From the values obtained with the three screens at both illuminations, the amount of change due to decrease in the amount of colored light coming to the eye and the amount due to induction by the white and black screens were calculated as follows. (*a*) From the number of degrees expressing the limits for a given color at standard illumination with a screen of the brightness of the color at that illumination was subtracted the number expressing its limit at decreased illumination with a screen of the brightness of the color at the decreased illumination. That this gave the number of degrees the zone of sensitivity was narrowed by the decrease in the energy of the stimulus may be said with the following qualification. If there is any influence upon color sensitivity of the local brightness-adaptation of the retina produced by the change in the general illumination, it is, of course, included in this effect. But, since this influence would have to be brought about by previous exposure to the illumination in question, it can be reduced to a minimum by guarding against an exposure to it for any considerable length of time. The effect of whatever adaptation there may be, however, can not be isolated or separated out from the above result, and the value expressing the amount the limit is narrowed by the actual decrease of the energy of colored light coming to the eye cannot, strictly speaking, be obtained. But it is probable that the adaptation effect is not sufficiently strong to influence the limits, since the sensitivity of the extreme peripheral retina falls off very abruptly from point to point. The difference, then, between the color limit obtained at standard illumination and the limit at decreased illumination, when in both cases there is no brightness induction from the screen, may be said to approximate the effect upon the limits produced by the decrease in the amount of colored light coming to the eye. (*b*) Figures can be obtained, however, from our results, which express the amount by which the zones are narrowed by the change in the inductive action of the white and black screens produced by decreasing the illumination, that are not open to theoretical questioning; for the influence of local brightness-adaptation, if there be any, is a constant for all screens at the same illu-

mination. If then, the number of degrees which expresses the limits of sensitivity for either the white or the black screen at decreased illumination is subtracted from the number expressing the limit with a screen of the gray of the brightness of the color at this illumination, the result will represent the extent to which the limit was narrowed by the action of induction alone. The results show in general the following facts:

1. At standard illumination, induction from the white screen narrows the limits of yellow and red; induction from the black screen narrows the limits of blue and green. The difference is in no case more than 4°.

2. At decreased illumination, the induction from the white screen narrows the limits of all the colors much more considerably than does the induction from the black screen.[1]

3. The values expressing the narrowing of the limits caused by decrease of illumination without induction are greatest in case of those colors which undergo maximum change of brightness in passing into the periphery, namely, for blue and red.

We have shown by the results of the preceding section, that the increased induction produced by decrease of the general illumination is greater for the white screen than for the black, and, by the results of this section, that this increase is effective to the extent of narrowing the limits of sensitivity to all colors from 5° to 12° with this screen. With the black screen, the limits were narrowed from 3° to 6°. At standard illumination, the limits were narrowed only from 1° to 4° with either the white or the black screens.

Results in detail are given in Tables IV. and V., taken from the temporal meridians of the observers whose observations are recorded in Tables I. and II. In column 1, Tables IV. and V., is given the stimulus. Column 2 shows the limit of sensitivity to the stimulus at standard illumination with a screen of a

[1] For observer *A* the results for green present an exception. At the decreased illumination used the green stimulus appeared bluish in the central retina. The induction of the black screen caused it to appear as a pale blue at a comparatively slight degree of excentricity. According to our definition of color limit, this point is the limit of green. It is, however, obvious that the exception is due rather to the qualitative than to the quantitative effect of brightness upon color.

gray of the brightness of the color at standard illumination; column 3 shows the limit with a white screen; and column 4 with a black screen. Column 5 shows the limit at decreased illumination with a screen of the brightness of the color at decreased illumination; column 6 shows the limit with a white screen; and column 7 with a black screen.

Table IV

A. Showing the Color Limits at Standard and Decreased Illumination (*a*) with Gray Screens of the Brightnesses of the Colors at the Illumination Used; and (*b*) with White and Black Screens

Stimulus	Standard Illumination			Decreased Illumination		
	Limit with Gray Screen of Brightness of Color at Standard Illumination	Limit with White Screen	Limit with Black Screen	Limit with Gray Screen of Brightness of Color at Decreased Illumination	Limit with White Screen	Limit with Black Screen
Yellow......	44°	42°	45°	43°	35°	43°
Green	37°	37°	34°	36°	31°	27°
Red........	43°	42°	44°	40°	31°	40°
Blue........	50°	50°	49°	48°	36°	43°

Table V

Observer *C*

Stimulus	Standard Illumination			Decreased Illumination		
	Limit with Gray Screen of Brightness of Color at Standard Illumination	Limit with White Screen	Limit with Black Screen	Limit with Gray Screen of Brightness of Color at Decreased Illumination	Limit with White Screen	Limit with Black Screen
Yellow......	49°	46°	50°	46°	36°	44°
Green	44°	42°	40°	41°	28°	33°
Red........	45°	41°	45°	41°	34°	41°
Blue........	56°	55°	53°	50°	38°	44°

Tables VI. and VII. have been compiled from Tables IV. and V. to show the following facts.

(1) How much the decrease of illumination narrowed the limits of color sensitivity by causing a decrease in the energy of the light waves coming to the eye. This was determined by subtracting the value of the limit at decreased illumination with the screen of a gray of the brightness of the color at decreased illumination from its value at full illumination with the gray screen of the brightness of the color at full illumination.

(2) How much the limits were narrowed by the action of the white and black screens at decreased illumination. This was ascertained by subtracting the values of the limit with the white and the black screen at decreased illumination from the value of the limit at decreased illumination with the gray screen of the brightness of the color at this illumination. (3) How much more the limits were narrowed by the white and the black screens at decreased than at full illumination. This was computed for the white screen, for example, as follows. The quantity, limit at decreased illumination for gray screen of brightness of color at decreased illumination, minus limit for white screen at decreased illumination, is subtracted from the

Table VI

A. Showing (1) How Much the Limits were Narrowed by Decrease in the Amount of Colored Light Coming to the Eye; (2) How Much They were Narrowed by Increased Induction of White and Black Screens at Decreased Illumination; and (3) How Much More They were Narrowed by Induction of White and Black Screens at Decreased Than at Full Illumination

Stimulus	How Much Limits were Narrowed by Decrease in Amount of Colored Light Coming to the Eye	How Much Limits were Narrowed by Induction of White Screen	How Much Limits were Narrowed by Induction of Black Screen	How Much More Limits were Narrowed by White Screen at Decreased than at Full Illumination	How Much More Limits were Narrowed by Black Screen at Decreased than at Full Illumination
Yellow......	1°	8°	0°	6°	3°
Green......	1°	5°	9°	5°	6°
Red........	3°	9°	0°	8°	3°
Blue........	2°	12°	5°	12°	4°

Table VII

Observer *C*

Stimulus	How Much Limits were Narrowed by Decrease in Amount of Colored Light Coming to the Eye	How Much Limits were Narrowed by Induction of White Screen	How Much Limits were Narrowed by Induction of Black Screen	How Much More Limits were Narrowed by White Screen at Decreased than at Full Illumination	How Much More Limits were Narrowed by Black Screen at Decreased than at Full Illumination
Yellow......	3°	10°	2°	7°	3°
Green......	3°	13°	8°	11°	4°
Red........	4°	7°	0°	3°	0°
Blue........	6°	12°	7°	11°	3°

quantity, limit at full illumination for gray screen of brightness of color at full illumination minus limit for white screen at full illumination. A similar computation was made for the black screen.

Results when a Gray Screen Matching the Color in Brightness at Standard Illumination is Used.—In these experiments a determination was made of the amount the limits of sensitivity are changed by the brightness induction caused by the alteration of the brightness relation between stimulus and screen with decrease of illumination, when a screen is used which matches the color in brightness at standard illumination. This determination was made as follows. An estimate was made of the amount the limits were narrowed by decrease of illumination when a screen of the brightness of the color at standard illumination is used for both standard and decreased illuminations. From this result was subtracted the amount the limits were narrowed by decrease of illumination when the screen is made in turn of the brightness of the color at standard and decreased illumination. The difference obtained represents the value sought. It is given in Table VIII.

TABLE VIII

A. SHOWING HOW MUCH THE COLOR LIMITS WERE NARROWED AT DECREASED ILLUMINATION BY THE INDUCTION OF THE SCREEN WHICH MATCHED THE COLOR IN BRIGHTNESS AT STANDARD ILLUMINATION

Stimulus	Screen of Brightness of Color at Decreased Illumination	Limit	Screen of Brightness of Color at Standard Illumination	Limit	Amount Limit was Narrowed by Change in Brightness Relation Between Stimulus and Screen Caused by Decreased Illumination
Yellow...	gray No. 3	43°	gray No. 2	41°	2°
Green ...	gray No. 5	36°	gray No. 8	29°	7°
Red	gray No. 50	40°	gray No. 24	33°	7°
Blue.....	gray No. 13	48°	gray No. 28	46°	2°

3. THE EFFECT OF THESE AMOUNTS OF INDUCTION UPON THE LIMEN OF COLOR AT DIFFERENT DEGREES OF EXCENTRICITY

We have shown the effect of decreasing the general illumination upon the color sensitivity of the peripheral retina with

gray, white, and black screens, by the effect on the limits of sensitivity. This is only an indirect means of estimating its influence, for the results obtained cannot be translated into terms of direct measurement, owing to the irregular decrease in sensitivity of the peripheral retina from the fovea outwards. In this section, we shall measure the influence of changes of illumination directly by the changes produced in the limen of sensation at various angles of excentricity. As in the previous section, measurement will be made of the effect upon sensitivity (1) of the decrease in the amount of colored light coming to the eye, produced by the decrease of illumination, (2) of the difference in the inducing power of the white and black screens, and (3) of the change in the brightness relation of stimulus to background.

To determine the first of these three points, a campimeter screen had to be selected that gave no brightness contrast with the stimulus. To provide for differences in the brightness of the colors at the different points observed for the two illuminations at which we worked, a preliminary determination of the brightness of the sensation at these points was made at both illuminations by the flicker method. The brightness of the screen was chosen in each case of the brightness of the color according to these determinations. To eliminate the effect of preëxposure, the stimulus previous to exposure was in every case covered by a gray of the brightness of the color for the illumination used at the point of the retina at which we were working. Thus no brightness after-image was carried over to exert an inhibitive action upon the color sensation. The stimulus was a disc compounded of sectors of the color and of the gray of the brightness of the color for the illumination used at the point of the retina under investigation. The proportions of the sectors were altered until the observer gave the judgment of just noticeable color. The average of judgments made in ascending and descending series was chosen as the final value of the limen. The difference between the limens at standard and decreased illumination was taken as the measure of the loss in intensity which the stimulus had sustained by the decrease of illumination.

The effect upon the color limen of the increased induction from the white and black screens was shown by the same method, with the exception that the white and black screens were substituted for the gray of the brightness of the color. The stimulus was a disc composed of sectors of color and gray of the brightness of the color at the angle of excentricity at which the determination was made.

The effect of the change in the brightness relation between the stimulus color and the screen produced by decrease of illumination was shown as follows. An estimate was made of the amount the limens are raised by the decrease of illumination when a screen was used for both standard and decreased illumination that had a brightness value equal to the color at standard illumination. From these results was subtracted the amount the limens were raised by decreasing the illumination when the screens were made in turn of the brightness of the color at standard and at decreased illumination. The difference obtained represents the value sought. These results are of particular importance because they show that the influence of the brightness of the surrounding field can not be eliminated even when a screen of the brightness of the color is used unless some means be had of maintaining the general illumination of the room constant.

Table IX. shows how much the limens of sensitivity were raised at the fovea and at points 15°, 25° and 30° from the fovea in the horizontal meridian on the temporal side by the decrease in the amount of colored light coming to the eye produced by the decrease in the general illumination. The results of this table may be generalized as follows:

1. The limen of color is higher in the periphery than in the center of the retina at both illuminations.

2. The limen of color is higher at decreased illumination that at standard illumination.

3. The direct effect upon the intensity of the sensation produced by decreasing the illumination is shown by the limen determinations to be inconsiderable. In the central retina, the difference is but 2° or 3°. In the peripheral retina at the points considered there is a difference of from 10° to 20°.

Table IX

A. Showing How Much the Limens of Sensitivity were Raised at the Fovea, and at Points 15°, 25°, 30° from the Fovea in the Horizontal Meridian on the Temporal Side by the Decrease in the Amount of Colored Light Coming to the Eye Produced by the Decrease in the General Illumination

Stimulus	Point on Horizontal Temporal Meridian at Which Limen was Taken	Limen at Standard Illumination with Screen of Brightness of Color at Standard Illumination	Limen at Decreased Illumination with Screen of Brightness of Color at Decreased Illumination	How Much Limen was Raised at Decreased Illumination
Yellow.......	0°	18°	20°	2°
	15°	22°	32°	10°
	25°	35°	40°	5°
	30°	50°	65°	15°
Green.......	0°	20°	20°	0°
	15°	27°	28°	1°
	25°	40°	50°	10°
Red.........	0°	9°	11°	2°
	15°	9°	13°	4°
	25°	17°	25°	8°
	30°	25°	45°	20°
Blue.........	0°	9°	10°	1°
	15°	10°	13°	3°
	25°	12°	15°	3°
	30°	20°	40°	20°

Table X

A. Showing the Color Limens at Standard and Decreased Illuminations with White and With Black Screens

Stimulus	Point on Horizontal Temporal Meridian at Which Limen was Taken	White Screen		Black Screen	
		Limen at Standard Illumination	Limen at Decreased Illumination	Limen at Standard Illumination	Limen at Decreased Illumination
Yellow...	0°	22°	25°	28°	30°
	15°	25°	50°	35°	45°
	25°	50°	80°	42°	60°
	30°	80°	125°	60°	90°
Green....	0°	22°	25°	28°	30°
	15°	26°	36°	35°	43°
	25°	30°	75°	75°	220°
Red......	0°	13°	20°	10°	14°
	15°	19°	35°	13°	19°
	25°	30°	55°	23°	35°
	30°	50°	330°	29°	58°
Blue.....	0°	17°	22°	10°	12°
	15°	25°	40°	12°	17°
	25°	35°	60°	18°	25°
	30°	40°	90°	30°	60°

Table X. shows the color limens at both standard and decreased illuminations when white and black screens are used, at the fovea and at points 15°, 25°, and 30° in the horizontal meridian on the temporal side.

Table XI. has been compiled from Tables IX. and X. to show how much greater the limens were for white and black screens at decreased than at full illumination; how much of the effect may be ascribed to the reduction of the amount of colored light coming to the eye; and how much to the increased induction of the screens. It will be seen from the results of this table that the loss of the sensation in intensity due to the increased brightness induction is much greater than that caused by the reduction in the amount of colored light coming to the eye.

Table XI

A. Showing How Much Greater the Limens were with White and Black Screens at Decreased Than at Standard Illumination and How Much of This Effect may be Ascribed to the Reduction in the Amount of Colored Light Coming to the Eye and How Much to the Increased Inductive Action of the Screens

Stimulus	Point on Horizontal Temporal Meridian at Which Limen was Taken	White Screen			Black Screen		
		Total Amount Greater	Amount Due to Decrease in Amount of Colored Light Coming to Eye	Amount Due to Increased Induction of Screen	Total Amount Greater	Amount Due to Decrease in Amount of Colored Light Coming to Eye	Amount Due to Increased Induction of Screen
Yellow...	0°	7°	2°	5°	12°	2°	10°
	15°	28°	10°	18°	23°	10°	13°
	25°	45°	5°	40°	25°	5°	20°
	30°	75	15°	60°	35°	15°	25°
Green ...	0°	5°	0°	5°	10°	0°	10°
	15°	8°	1°	7°	16°	1°	15°
	25°	35°	10°	25°	180°	10°	170°
Red.....	0°	11°	2°	9°	5°	2°	3°
	15°	26°	4°	22°	10°	4°	6°
	25°	38°	8°	30°	18°	8°	10°
	30°	305°	20°	285°	33°	20°	13°
Blue.....	0°	13°	1°	12°	3°	1°	2°
	15°	30°	3°	27°	7°	3°	4°
	25°	48°	3°	45°	13°	3°	10°
	30°	70°	20°	50°	40°	20°	20°

It was shown in Table III. that quite a great deal of brightness induction is caused by the change in brightness relation between color and screen produced by decreasing the illumination. Table VIII. shows how much this induction narrows the limits of sensitivity to the four colors used. Table XII. shows how much the limens are raised when the illumination is decreased by the inductive action caused by the change in the brightness relation between stimulus color and gray screen of the brightness of the color at standard illumination.

Table XII

A. Showing How Much the Color Limens were Raised at Decreased Illumination by the Induction of the Screens Which Matched the Color at Standard Illumination

Stimulus	Point on Horizontal Temporal Meridian at Which Limen was Taken	Limen with Screen of Brightness of Color at Decreased Illumination	Limen with Screen of Brightness of Color at Standard Illumination	Amount Limen was Raised by Change in Brightness Relation Between Stimulus and Screen Caused by Decrease of Illumination
Yellow.......	0°	20°	20°	0°
	15°	32°	32°	0°
	25°	40°	40°	0°
	30°	65°	116°	51°
Green.......	0°	20°	20°	0°
	15°	28°	40°	12°
	25°	50°	190°	140°
Red.........	0°	11°	11°	0°
	15°	13°	24°	11°
	25°	25°	48°	23°
	30°	45°	150°	105°
Blue.........	0°	10°	12°	2°
	15°	13°	16°	3°
	25°	15°	23°	8°
	30°	40°	55°	15°

4. The Influence of Change of Illumination upon the Action of the Preëxposure on the Limens and Limits of Color

The brightness of the preëxposure exerts an influence upon the color observation because the eye carries over an after-image from the preëxposure into the color observation. If, for example, the preëxposure is to black, a white after-image is

aroused which fuses with the succeeding color sensation and strongly reduces its saturation. The effect of preëxposure is especially strong in the peripheral retina because a very strong brightness after-image is aroused in the peripheral retina by a very short period of stimulation. It is very difficult for the writer to predict from the data she has at hand with regard to the effect of change of illumination upon the sensitivity of the peripheral retina to the brightness after-image just what will be the effect of change of illumination upon the action of preexposure on the color sensitivity of the peripheral retina. But even though there be no change in the sensitivity of the peripheral retina to the brightness after-image with change of illumination, it is obvious that there will be some effect of the change of illumination because of the change in the brightness relation of the preëxposure card to the colored stimulus. In case the stimulus light is gotten by reflection from pigment surfaces, this change of brightness relation is due to the shift in the brightness of the colors produced by the change in the illumination. In case transmitted light is used as stimulus, the brightness of the stimulus color is independent of changes in illumination and will remain constant; but a change in the brightness relation of stimulus to preëxposure will occur because the preëxposure will lighten or darken with change of illumination. The writer hopes to make the quantitative investigation of this point the subject of a future study. At present she can only point out that if a guarantee is wanted that the effect of the brightness of the preëxposure is eliminated from the results of the observation, the preëxposure must be to a gray of the brightness of the color and the illumination of the room must be kept constant.

IV. Conclusion

The foregoing results show how strongly the changes in the illumination of the visual field influence the color sensitivity of the peripheral retina, particularly when the stimulus is surrounded by a white field. They also show that the influence of surrounding field can not be eliminated even by means of a campimeter screen of the brightness of the color unless some

means be had of keeping the general illumination of the room constant. It is obvious without further comment how important it is that a method be devised to standardize this factor. The preceding experiments indicate that without this standardization, no experiment can be repeated from time to time under the same conditions relative to any one of the brightness factors that influence color sensitivity. Results thus obtained are far from comparable. As was stated earlier in the paper a method of standardizing was described in an earlier paper in this volume of the REVIEW.[1]

[1] See footnote, 2, p. 1.

It was the writer's intention to have had the present article precede the one in which the method of standardizing is described, but owing to limited space in the July number the Editor was compelled to use for that number the shorter article.

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TESTS FOR THE EFFICIENCY OF THE EYE UNDER DIFFERENT SYSTEMS OF ILLUMINATION AND A PRELIMINARY STUDY OF THE CAUSES OF DISCOMFORT.*

BY C. E. FERREE.

Synopsis:—Besides outlining (I) the problem which confronts the investigator who would determine the effects of various lighting systems on the eye, this paper discusses: (II) the scale or general level of efficiency of the eye under different systems of lighting, with brief comments on the conventional tests for the efficiency of the eye such as, (*a*) color discrimination, (*b*) brightness discrimination, (*c*) visual acuity—the latter tests, modified, it is contended are adequate for the determination of the general level of efficiency of the unfatigued eye; (III) loss of visual efficiency as the result of a period of work—here it is contended that each of the aforementioned tests fails to show a true loss of visual efficiency, and a new test is described. The paper is concluded (IV) with a brief statement of some of the causes of ocular discomfort under various conditions, and a description of a method of making a comparative estimate of discomfort.

I. INTRODUCTION.

In 1911 the American Medical Association appointed a committee to study the effect of different lighting systems on the eye. The writer was asked to share in the work of this committee. The problem presented to him was to furnish tests that would show the effect of different lighting systems on the eye and more especially to devise, if possible, a test that would show a loss of efficiency as the result of three or four hours of work under an unfavorable lighting system. It is the purpose of the following paper to give a preliminary report of the work that has been carried on by the writer in this field during the past year.

Confronting the problem of the effect of lighting systems on the eye, it is obvious that the first step toward systematic work is to obtain some means of making a definite estimate of this effect. The prominent effects of bad systems of lighting are loss of efficiency, temporary and progressive, and eye discomfort. Having devised methods which after six months of testing he has found to be accurate and practicable, the writer has under-

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taken to determine (1) the lighting conditions that give in general the highest level or scale of visual efficiency, (2) the conditions that give the least loss of efficiency for continued work, and (3) the conditions that cause the least discomfort. This plan of work, it is scarcely needful to remark, will involve a wide range of experimentation. The crux of the problem, as the writer conceives it, is, however, to secure reliable methods of estimating effect. Having these methods, the factors whatever they may be, intensity, quality, position of light relative to the eye, etc., can be varied one at a time and the effects be determined. From these effects it should not be difficult to ascertain what lighting conditions are best for the eye and what is the relative importance of the factors that go to make up these conditions. Further it should be possible on the practical side to test out and perfect a lighting system, so far as its effect on the eye is concerned, before we put it on the market.*

In this report nothing more will be attempted than to indicate what methods may be used in the three steps of the problem as outlined above.

II. THE SCALE OR GENERAL LEVEL OF EFFICIENCY OF THE EYE UNDER DIFFERENT SYSTEMS OF LIGHTING.

A general survey of the field shows that at different times the following tests have been used in one capacity or another for determining the efficiency of the eye: brightness discrimination, color discrimination, and visual acuity. No extensive use, if any at all, has been made of any of these with the exception of visual acuity in connection with problems of the type here considered, but the fitness of their application in some form to such problems is evident at a glance. If the eye's efficiency is to change at different times and under different conditions of lighting, it should be manifested in changes in brightness discrimination, color discrimination, or visual acuity. The first step in our work would, then, seem to be to devise for these points tests which are sufficiently sensitive for use in work of the kind we have in hand. The general nature of these tests is too familiar to need detailed mention here. A few special points may, however, be given in passing. (1) The threshold or limen test is the most sensitive and practical

* This latter point was suggested to the writer by reading Dr. Ives' discussion of this paper (p. 57).

for color sensitivity. In making this test the pre-exposure[1] and the surrounding field[2] should be of a gray of the brightness of the color at or near its threshold value. Further, the illumination of the room must be kept constant from test to test.[3] If the colored light is to be obtained by reflection, disks of standard

[1] By pre-exposure is meant what the eye rests on immediately preceding its stimulation by color. It is obvious that there must always be some pre-exposure and, unless care be taken to eliminate its effect, it will influence the eye's sensitivity to color. Even closing the eye, as is often done before stimulating by color, is the equivalent of giving a black pre-exposure. All color must of course be eliminated from the pre-exposure. It should also be of the same brightness as the color by which the eye is to be stimulated. If not it gives a brightness after-image which mixes with the succeeding color impression and reduces its saturation. This reduction of saturation takes place apparently at some physiological level posterior to the seat of the positive, negative, and contrast color processes commonly supposed to be located in the retina. (See Ferree and Rand: "The Fusion of Brightness with Color—The Locus of the Action," *Journal of Philosophy, Psychology and Scientific Methods*, VIII, 1911, p. 294.) If the pre-exposure is lighter than the color it adds by after-image a certain amount of black to the succeeding color impression and, if darker, it adds a certain amount of white. Since white inhibits color more than black, the effect of a dark pre-exposure is to reduce the sensitivity to color more than the effect of a light pre-exposure. But since both white and black as after-effect reduce the sensitivity to color, the eye is rendered more sensitive when no after-image is given, *i. e.* when the pre-exposure is of the same brightness as the color. The pre-exposure therefore should be to a gray of the brightness of the color. No brightness after-image will be added thereby to the succeeding color impression to modify either its saturation or color tone.

[2] When the surrounding field is either lighter or darker than the color, brightness is induced by contrast across the colored surface. When the surrounding field is lighter than the color, a certain amount of black is induced, and when darker, a certain amount of white is induced. As stated above, the mixture of this white or black with color, although it does not alter the amount of colored light coming to the eye, reduces the saturation of the color. The effect of brightness contrast can be eliminated only by making the brightness of the surrounding field a gray of the brightness of the color. This can be done by means of a gray screen around the color, or by a larger gray disk in case a color mixer is used.

[3] In case the colored light used for the stimulus is obtained by reflection from a pigment surface, a change in the general illumination of the field of vision affects the results of the sensitivity tests in the following ways. (1) It changes the amount of colored light coming to the eye. (2) By changing its brightness adaptation it changes the sensitivity of that part of the retina upon which the colored light falls. (3) By changing the sensitivity of the eye to brightness after-image and contrast, it changes the amount of brightness added to the color as the result of pre-exposure and surrounding field, and therefore changes the effect of pre-exposure and surrounding field upon the color impression. Moreover, the effect of pre-exposure and surrounding field cannot be eliminated even when both are made of the brightness of the color for some given illumination, unless that illumination be kept constant throughout the test for, when it changes, the brightness of the color and of the grays used as pre-exposure and surrounding field does not change in equal amounts; hence, the brightness equality which is needed cannot be maintained. In case the colored light is not gotten by reflection from a pigment surface but is obtained from monochromatic sources from standard filters or from the spectrum, only the last two of the factors stated above influence the results of the tests for color sensitivity. In the tests made by the writer, the general illumination was rendered constant by methods to be described later in the paper.

Although for the purposes of this work the tests for color sensitivity could never be conducted in the dark-room, still it may be of general interest to note at this point that the elimination of the effect of pre-exposure and surrounding field cannot be accomplished in work on color sensitivity done in the dark-room, because in the dark-room the pre-exposure and surrounding field cannot be made of the brightness of the color. They will always therefore exert an effect on the color impression. Moreover since the colors all differ in brightness, this effect will be exerted in different amounts on the different colors. That is, the amount of brightness added by after-image or contrast depends upon the amount of brightness difference, respectively, between pre-exposure and color and surrounding field and color. As stated above this amount, when working in the dark-room, will be different for the different colors. For this reason and also because even the same amount of brightness excitation acts with different degrees of strength upon the excitation set up by the different colors, it is especially important that no work on the comparative sensitivity of the retina to the different colors should be done in the dark-room. It should be done in a light room of a constant intensity of illumination and with pre-exposure and surrounding field in each case of the brightness of the color to be used. In this way alone can all the factors which influence the sensitivity of the retina, extraneous to the source of light, be eliminated.

colored and gray papers (*e. g.*, the papers of the Hering series) may be used on a color mixer.[4] If, on the other hand, it is desirable to use the light of the spectrum or the light transmitted through standard filters, the colored light may be cut down to the threshold value by means of a sectored disk, the sectors of which should be covered with a gray of the brightness of the color at or near its threshold value. (2) For brightness discrimination also the threshold or limen test is the most sensitive and practical, but when made in a well-illuminated room, it becomes in effect a test for a just noticeable difference. This test may be performed at different points in the brightness scale, *e. g.*, when the standard is black, near mid-gray, or white. As before, disks of standard papers may be used on the color-mixer, or the light from a given source may be varied by means of a sectored disk.[5] (3) Visual acuity tests of the Snellen type, especially when used in work in which it is required to make successive tests on the same person, are open to the following objections. (a) The judgment is in terms of recognition. A letter may be recognized when it is not seen clearly. In any judgment based on the recognition of even a single letter, memory plays an important role. It is, so far as the writer knows, impossible to standardize this memory factor and to obtain results strictly in terms of acuteness of vision. (b) The test card is made up of quite a long series of letters. As the test progresses the letters are memorized more and more completely. It is practically impossible to eliminate this progressive error when a number of successive judgments have to be

[4] In making the tests with reflected light, two sets of disks are mounted on a color mixer (*a*) an outer disk of gray of the brightness of the color to be used, and (*b*) an inner disk made up of this gray and the disk of color. To the inner gray disk, varying preportions of the color are added until the threshold value or just noticeable color is obtained. To facilitate the judgment of just noticeable color, the inner disk of gray plus color is compared with the outer disk of gray as a standard. Since both grays are of the brightness of the color, the addition of the colored sector to the inner disk produces no change of brightness either to confuse the judgment of noticeable color, or to affect the intensity of the color excitation actually aroused. In getting the threshold value, the method of ascending and descending series should be used, that is, beginning with equality, the variation is towards noticeable difference and beginning with a difference greater than noticeable, the variation is towards equality. An average of the two sets of results is taken for the threshold value.

[5] When the test is made with reflected light two sets of disks, an outer and an inner, are mounted on the color mixer. Each set is made up of one white and one black disk. Both sets of disks are set at the point in the brightness scale from which the variation towards white or black is to be made. One is kept constant and the other is changed until the judgment different is given. In making the judgment the method of ascending and decending series is used and the results are averaged for the difference limen. This difference limen is taken as the measure of the observer's sensitivity to brightness or white light.

made as is the case before a final result is reached in any single visual acuity test and as is especially the case when a number of successive tests have to be given to the same person, which happens in much of the work involved in the solution of the problem here proposed. It might be supposed that the memorization of the series could be broken up by using in each successive judgment in a single test or in the successive tests, as the case may be, cards having a different distribution of the letters in the series. Considerable inconvenience would, however, be involved in giving the tests in this way and besides no guarantee could be had that each judgment would present the same degree of difficulty. That is, the series is made up of similar and dissimilar letters. The dissimilar letters can be distinguished from each other with less difficulty than the similar. It is practically impossible to distribute the letters so that the individual tests may be equally rigorous. This objection can, of course, be eliminated in part by a careful selection of the test letters, but not entirely because a series of letters uniformly similar cannot be found. (c) The Snellen series contains quite a large number of letters. The eye is found to fatigue and vision to blur before the series is completed. This introduces an error which it is practically impossible to render constant.

All of the above objections were eliminated in the tests finally adopted by us by changing the type of judgment and by making the test object in one case two parallel vertical lines stamped 1 mm. apart on a white card[6] and in another the letters li printed in small type.[7] In using these cards the observer's acuity of

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[6] The card is mounted on a sliding carrier which runs on a track made of two meter rods fastened end to end on a folding base. The base is mounted on adjustable stands fastened to a table. When making the test the apparatus is so adjusted that the track carrying the test card is just below and close to the observer's eye. In order that the observer's head may be held steady he is required to bite an impression of his teeth, previously made and hardened in wax on a mouth-board, which is rigidly fastened by a heavy iron rod and accessories to the table supporting the track and carrier.

[7] Besides the letters li the writer would recommend the following figures as test objects.

(1) . The test is to distinguish clearly the dot at the center. A test object in the shape of a cross has the advantage of affording a steady control of fixation. According to photographic records of involuntary eye-movement, where a variety of fixation objects has been used, the cross is found to give the best control of fixation.

(2)  or . In these figures also the test is to distinguish the dot clearly. The former figure, however, is a little too complicated. There is both a tendency to lose the dot and for the lines to run together on either side. A simpler criterion gives an easier and safer judgment. Doubtless with a little effort other figures can be found possessing still greater merit as test objects.

vision is determined by the distance at which he can just clearly distinguish in every detail the two test objects. The results are thus rendered directly in terms of clearness of vision, and there are no progressive errors introduced by memory and fatigue.

We have good reason to believe that the brightness sensitivity, color sensitivity, and visual acuity tests rendered sensitive and adapted to our purpose in the manner described above will serve as a measure of the general level of efficiency of the unfatigued eye under different systems of illumination. For example, they show considerable difference in result when the tests are given under three types of lighting now in use: namely, systems of direct lighting, systems of indirect lighting, and daylight. In each of these cases, the intensity of the light falling on the test object measured in foot-candles is kept the same. The tests can not, however, be depended upon to show a loss of efficiency of the eye as a result of three or four hours of work even under a very unfavorable lighting system.

III. LOSS OF EFFICIENCY AS THE RESULT OF A PERIOD OF WORK.

We have no reason to believe that the brightness and color sensitivity tests have failed to show that the eye loses in efficiency as the result of a period of work under an unfavorable lighting system because of any fault in the tests. The tests used are the product of several years of study by the writer of the sensitivity of the eye to brightness and color and of the factors that influence this sensitivity. There is doubtless very little, if any, loss of sensitivity during this length of time. In fact it is commonly believed that the brightness and color processes are compensating in nature. The case is quite different, however, with the conventional visual acuity test, or even with the modification of it described above. Although brightness and color sensitivity are factors influencing the visual acuity test, still in every case to which it may be applied, it is predominantly a test of the refracting mechanism of the eye and its muscular control. In fact our results for the tests of brightness and color sensitivity teach us that when applied to the case in hand in which there has been no change in the quality and intensity of the illumination or of the refracting mechanism from the beginning to the close of work,

the results of the visual acuity test may be ascribed practically entirely to changes in the muscular control of the refracting mechanism, or at least to changes in the muscular control of the eyes as a whole.[8] Now the visual acuity test, when it is confined to a momentary judgment of clearness of vision, is not adapted to show a loss in muscular efficiency because, although this efficiency may have been lowered enormously, it may rise momentarily under the spur of the test to its usual level, or at least to the level obtaining at the beginning of work. Just as the runner may, under the spur of his will, equal in the last lap of his course the highest speed he has attained at any other point in the course; so may the flagging muscles of the eye be whipped up to their normal power long enough to make the judgment required by the visual acuity test. It was the feeling of all our observers that at the close of work under the system of direct lighting installed in our laboratory the eye had lost heavily in efficiency. A great deal of discomfort was felt. The test was painful and was accomplished only with decided strain. Still the judgment could be made apparently with as much accuracy as at the beginning of work. But just as the runner finishing his course cannot long keep up his extra burst of speed, so might we expect that the eye cannot sustain its extra effort. This analogy led the writer to continue the visual acuity test through an interval of time. After considerable experimentation an interval of three minutes was chosen as best suited for our purpose. Our surmise proved to be correct. The fatigued eye cannot keep up its extra effort. The results of the test showed an enormous loss of efficiency as

[8] Before the writer would speak with full certainty, however, that the retina loses none of its power to function for color and brightness sensation during the above stated period of work, he would feel it necessary to perform another kind of test for color and brightness sensitivity. This test has been devised by him especially to meet the needs of this problem. In this test the element of time is introduced. It is possible that the retina may have lost in power to give color and brightness sensation as the result of a period of work even when the conventional test based on a momentary judgment, shows no loss of sensitivity. That is, it may be more susceptible to fatigue as the result of the preceding work. To determine this, a fatigue test should be run at the beginning and close of work. For color this may be done in two ways. (1) A given amount of colored light may be used and the time required for the eye to become completely exhausted or insensitive to this color may be determined. The difference in time required for this amount of fatigue to take place at the beginning and at the close of work will represent how much the retina has lost in its power to function for color. (2) The experiment need not be continued until complete exhaustion takes place. The amount of exhaustion that has taken place in a given interval of time can be measured. As before, this can be done at the beginning and at the close of work and the results can be compared to find out how much the retina has lost in power to give color sensation.

the consequence of three hours of work under the system of direct lighting, while in daylight practically no loss was shown.

In detail the test is as follows. When the observer is required to look at the test card for three minutes, the test objects, even when the eyes are fresh, are not seen clearly for the whole time. The muscular effort required to keep the eyes adjusted for clear vision cannot be sustained steadily for that length of time. The test objects are seen alternately as clear and blurred. The time they are seen clear and blurred is recorded on a rotating drum upon which a line registering seconds is also run. From this record the ratio of the time seen clear to the time seen blurred is determined. This ratio may be fairly taken as a measure of the efficiency of the eye at the time the test is taken. In applying the test to our problem the record is taken at the beginning and at the close of work, and the ratios of the time clear and the time blurred are compared for the two cases to determine how much the eye has lost in efficiency as a result of work. Two values were chosen for the distance at which the test card was placed from the eye: (a) the maximal distance at which the test objects could be seen clearly in the momentary judgment, and (b) a distance less than this. The latter distance was chosen because for the maximal distance towards the close of the test, even when the eyes were fresh, the value of the time blurred became, it was thought, excessively high. Results for the two distances, therefore, give probably a fairer expression of the loss in efficiency than for the one.

The problem dealing with loss of efficiency as the writer has conceived it presents two phases. We may investigate (a) whether the eye shows a loss of efficiency after three or four hours of work under a given lighting system, and (b) whether there is a progressive loss of efficiency in working several months or years under a given lighting system. Only the first part of this investigation has been attempted thus far in our work and it has been undertaken, not so much for the purpose of making an exhaustive study of loss of efficiency under a given set of conditions, as it has been to get a sensitive and practical method of detecting loss of efficiency. In order to determine whether the method we have described is practical and sufficiently sensitive for our purpose, tests should be made on a

large number of people under a wide range of lighting conditions. We have not as yet made tests under a wide range of lighting conditions. We have chosen rather to begin with three broad types of illumination now in general use; systems of direct lighting, systems of indirect lighting, and daylight. Types based upon the distribution of light have been selected because it has seemed to the writer, both from his own work and from a survey of the work done by others, that distribution or diffuseness of light is the most important factor we have yet to deal with in our search for conditions that give minimum loss of efficiency and maximum comfort in seeing. The quality of the light and its intensity at the source are already pretty well taken care of, apparently at least better taken care of in general practise, relative to their importance to the eye, than is distribution. A detailed report of our results will not be given in this paper. The following results selected as typical from a large number of observations are appended, however, to show how the efficiency of the eye as measured by the above test falls off as the result of three hours of work under a system of direct lighting as compared with daylight.

The tests were conducted in a room 30.5 feet (9.29 m.) long, 22.3 feet (6.797 m.) wide and 9.5 feet (2.895 m.) high. The daylight illumination came from six windows, all on one side provided with thin white curtains to secure the necessary control. The artificial lighting[9] was accomplished by means of two rows of fixtures of four fixtures each. Each row was 6 feet (1.828 m.) from the side wall and the fixtures were 6 feet apart. Each fixture was supplied with two 16 candle-power carbon lamps 29 inches (0.736 m.) from the ceiling with a white porcelain reflector 16 inches (0.406 m.) in diameter fastened directly above. The daylight tests were made at 9 A. M. and 12 M. Between these limiting times, the observer was required to read pages of type, uniform in size, printed upon paper of uniform texture of surface and of uniform reflecting power. The tests for the system

[9] This room gave the impression of being brilliantly lighted. The writer was amazed to find, however, that only 2.5 foot-candles of light were received on the test card placed about midway between two of the rows of lights and midway between two sets of fixtures. The walls and ceiling of the room were of plaster, natural finish, and the floor of dark tiling. Before our tests were taken, the walls and ceilings were painted white which nearly doubled the light received on the test card.

of direct lighting were taken at 7 P. M. and 10 P. M. During the interval intervening, the observer was required to read type of the same size and printed on the same paper as was used in the daylight work. The reading was done in each case at exactly the same spot in the room as at which the tests were made. The intensity of illumination was also in both cases made as nearly equal as it was possible to do by methods now available.[10] The two tests were always given on successive days but one. In order to guarantee that the observer's physical and optical condition should be as nearly the same for the two tests as it was possible to obtain, he was required to rest during the day immediately preceding each test. Since the li test has proven to be the more sensitive, results will be given for it alone in the following table. Column 1 of this table gives the time of day at which the work was done and the tests were made. Column 2 gives the type of test. Column 3 gives the distance of the test card from the eye. As stated earlier in the paper, two distances were used; one the maximum at which the test object could be seen clearly, the other a distance less than this. Division A of the table gives the results for the former distance; division B, for the latter. Columns 4 and 5 respectively, give the number of times the test object was seen clear and unclear. Column 6 gives the number of seconds in the three minutes that the test object was seen clear, and

[10] In order to equalize the intensity of illumination, a method of measurement is required. Two methods were used by us; photometry, and a more delicate method based upon the sensitivity of the peripheral retina to brightness contrast. In case of the former, a Sharp-Millar portable photometer was used. The light falling upon the test card was measured in foot-candles and was made equal for each type of lighting. Full details of the latter method will not be given here. As stated above it is based upon the extreme sensitivity of the peripheral retina to brightness contrast, especially to the induction by a white screen. To apply the method, some given illumination is taken as standard. The amount of black induced by a white campimeter screen upon a 15 mm. area of some medium gray, (*e. g.* Hering gray No. 14) at an excentricity of 25 deg. in the temporal meridian, is measured. This amount of contrast is taken as the index of that illumination. To duplicate the illumination at any succeeding time, the intensity is varied until the same amount of contrast is induced by the white screen on the gray at the 25 deg. point, for the same observer. This method was devised in the writer's laboratory and he has found by repeated trials that, although it is not so convenient for many of the purposes for which the photometric method is used, it is many times more sensitive than the traditional photometric method. The Sharp-Millar photometer, like other photometers, is insensitive for the determination of the illumination of a room by daylight. This is because the standard field illuminated by the tungsten lamp is deep orange in color, while the comparison field illuminated by daylight is clear white. This difference in color tone makes the judgment of brightness equality difficult to make and renders the instrument extremely insensitive for daylight work.

column 7 the number of seconds unclear. Column 8 gives the ratio of the total time clear to the total time unclear. This ratio as stated earlier in the paper expresses the efficiency of the eye for clear seeing for an interval of three minutes at the time at which the test was taken.

TABLE I.

Showing How the Eye Falls Off in Efficiency as the Result of Three Hours of Work under a System of Direct Lighting as Compared with Daylight. In Division A the Test Card is Put at the Maximal Distance at Which the Test Object Could be Seen Clearly; in Division B, at a Distance Less than This.[11]

Time of day	Test	Distance of card from eye cm.	Number of times clear	Number of times unclear	Total time clear sec.	Total time unclear sec.	Total time clear ÷ Total time unclear
A.							
9 A. M.	li	102	15	15	105.6	78.4	1.4
12 M.	li	102	15	14	103.1	76.9	1.33
7 P. M.	li	75	18	18	119.7	60.3	1.98
10 P. M.	li	75	15	15	55.4	124.6	0.44
B.							
9 A. M.	li	92	14	13	136.8	43.2	3.16
12 M.	li	92	12	12	134.9	45.1	2.99
7 P. M.	li	65	24	23	141.8	38.2	3.7
10 P. M.	li	65	17	17	75.5	104.5	0.72

[11] It will be noticed in the table that the ratio total time seen clear ÷ total time seen unclear is smaller for the test both at the beginning and at the close of work in division A where the maximal distance at which the test object could be seen was used, than in division B where a distance less than this was used. This is just what should be expected from the nature of the test. For it may be said that, within limits, the nearer the object is to the eye the greater is the proportion of time it should be seen clearly; and, conversely, the farther the object is from the eye the smaller is the proportion of time it should be seen clearly. It will also be noticed that the ratio is slightly larger when the tests are made under the system of direct lighting than when made under daylight. The explanation of this, too, is found in terms of the distances that were chosen for the test object. These distances, relative to the maximal distance, were chosen shorter for the artificial light than for daylight. This was done because of the large falling off in the ratio gotten for the test at the close of work under the artificial light. Had the first of the two distances used in these tests, for example, been chosen as near to the maximal distance for the artificial light as it was for daylight, the result of the test made at the close of work would have been that, after the first interval seen as clear, the test object would have been seen unclearly during the remainder of the test. At first glance one might be tempted to think that the difference in the scale of magnitude for the two ratios, is due to some inequality in the intensity of the illumination that was given by the two systems of lighting. It is obvious on reflection, however, that the intensity of illumination can have little or nothing to do with the scale of magnitude of these ratios. The intensity of the illumination influences the maximal distances at which the test object can be seen clearly but the scale of magnitude of the ratio, time clear to time unclear must depend primarily upon how near the distance chosen for the test object is to the maximal distance. (This principle, it is obvious, does not affect the comparison of the ratios obtained at the beginning and close of work under a given lighting system for the dis-

(*Continued on following page.*)

In order to give a typical representation in graphic form of the effect of three hours of work on the efficiency of the eye in daylight and under the system of direct lighting, estimated in terms of the test we have described, the results of the above table are given in the form of a curve. In constructing this curve the length of time of work is plotted along the abscissa and ratio of the time the test object is seen clear to the time unclear, is plotted along the ordinate. Each one of the large squares along the abscissa represents an hour of work, and along the ordinate an integer of the ratio. Figure I shows the result of division A and figure II for division B of the table. An inspection of these

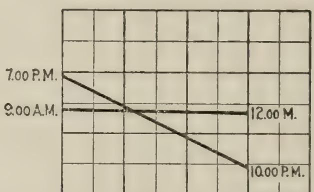

Fig. I.—Curve for division A of the table. Showing how the eye falls off in efficiency for three hours of work under a system of direct lighting as compared with daylight.

curves shows that the efficiency of the eye measured by the ratio of the time the test objects are seen clear to the time seen unclear, falls off rapidly for the system of direct lighting but scarcely at all for daylight.

Although it has been the purpose of this paper merely to out-

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tance, once it is chosen for that system, is kept the same or both tests). As further proof that the difference in the intensity of illumination had nothing whatever to do with this result, the intensity of illumination was carefully determined immediately before and after these tests and, if the readings showed any inconstancy in the illumination, the results were discarded and new tests were made. The above explanation should be borne in mind also in examining the curves plotted from the results of the table. The curve for division B of the table, for example, begins at a higher point on the ordinate than for division A; and the curve for the artificial illumination starts at a higher point than the curve for daylight.

It is scarcely necessary to point out that neither the scale of magnitude of ratio nor the point at which the curve starts is of any considerable consequence for our work. The important thing is not how large is the ratio at the beginning of work, but how much it falls off as the result of work. In fact the magnitude of ratio need not be taken into account at all any further than that it chances to be a coincident result of a condition that seems to render our test more sensitive. That is, our results seem to show that the ratio falls off more when the distance chosen for the test object is not too near the maximal distance. In future work, therefore, more care should be taken probably than was exercised in this preliminary study to choose the distances for the test object so that in case of each lighting system employed they shall sustain the same ratio to their corresponding maximal distances.

line and in part to demonstrate a set of tests, a word of discussion and interpretation of the results we have reported may not be out of place here. Since the visual acuity test (given under constant quality, intensity and distribution of light) is a test largely of the refractive mechanism of the eye and its muscular control and since the refractive mechanism could not have changed during three or four hours of work, the obvious indication of the above result is that the loss of efficiency sustained by the eye in these experiments is a loss in muscular efficiency. This conclusion is borne out also by the fact, stated earlier in the paper, that the direct tests of the efficiency of the retina, namely, the test for brightness and color sensitivity did not show conclusively any loss.[12] Moreover, the conlusion is in line with current conception. In current theory the retina is considered as a mechanism more or less compensating in its action, while

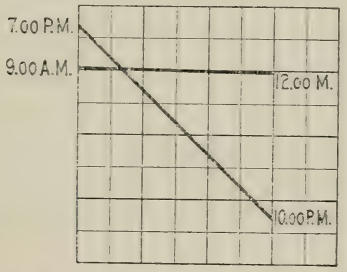

Fig. II.—Curve for division B of the table. Showing how the eye falls off in efficiency as the result of three hours of work under a system of direct lighting as compared with daylight.

the muscles of the eye are not so considered. The following reasons are suggested why the muscles of the eye giving both fixation and accommodation should be subjected to a greater strain by the system of direct lighting than by daylight. (1) The bright images of the electric bulbs falling on the peripheral retina which is in a perpetual state of darkness adaptation as compared with the central retina and is therefore extremely sensitive in its reaction to such intensive stimuli, sets up a reflex tendency for the eye to fixate them instead of the letters which the observer is engaged in reading. (2) Likewise, a strong reflex tendency to accommodate for these brilliant sources of light all at differ-

[12] This statement is also subject to the foot-note appended to the earlier statement.

ent distances from each other and from the lettered page, is set up. (3) These brilliant images falling upon a part of the retina that is not adapted to them causing as they do acute discomfort in a very short period of time,[13] doubtless induce spasmodic contractions of the muscles which both disturb the clearness of vision and greatly accentuate the fatiguing of the muscles. The net result of all these causes is excessive muscular strain which soon shows itself as a loss in power to do work. In the illumination of a room by daylight with a proper distribution of windows, the situation is quite different. The field of vision contains no bright sources of light to distract fixation and accommodation and to cause spasmodic muscular disturbances, due to the action of intensive light sources upon the dark adapted and sensitive peripheral retina. In daylight the light waves have suffered innumerable reflections and the light has become diffuse. The field of vision is uniformly illuminated. The illumination of the retina, therefore, falls off more or less uniformly from fovea to periphery as it should in order to permit of fixation and accommodation for a given object with the minimum amount of strain.

It is not our purpose to contend in this report that distribution is the only factor of importance in the illumination of a room. The intensity and the quality of the illumination must also be taken into consideration. To test the relative effect of these factors upon the working power of the eye, records would have to be taken when each was varied in turn and the other two maintained constant. In the results shown in the above tables the intensity alone was constant in the two cases. Both the quality and the distribution were different in the direct lighting system and the illumination by daylight. The difference in the results obtained will have, therefore, to be attributed both to

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[13] There is no doubt in the writer's mind that the eye-discomfort experienced as the result of work under an unfavorable system of lighting is not by any means all muscular. The "sandiness" passing over into a stinging, stabbing pain which comes early in the experience of discomfort seems to be conjunctival. And while the retina itself is apparently insensitive to pain from mechanical stimulation, still when exposed to a source of light of a brilliancy to which it is not adapted, a painful reaction is produced which can scarcely be considered muscular. For example, after confinement for some time in a dark-room exposure to ordinary daylight is painful to the normal eye. That this is not entirely muscular can be shown by the fact that a similar reaction is experienced when the ciliary and iris muscles are paralyzed by atropine. The reaction is also experienced by aphakial subjects whose lenses have been so long removed that muscular atrophy must have taken place.

difference in the distribution and to difference in the quality of the illumination. In our tests comparative of the systems of direct and indirect lighting, the results of which will be reported in a later paper, clear tungsten lamps will be used in both cases. The intensity will be made the same and the quality of the light will be approximately the same. The distribution or diffusion alone will be different. Whatever difference in result we get in these two cases can, therefore, with reasonable certainty be attributed to the differences in the distribution of light.

With regard to the effect of varying the intensity of illumination, our results show nothing; with regard to the effect of varying quality, nothing in isolation; and with regard to distribution, we have data only for such differences as are found in the three types of illumination now in general use. In later work, however, the analysis along these lines will be completed. We hope on the laboratory side, to make a systematic study of the effect of wide ranges of variation of each of the factors in turn. It will be comparatively easy, for example, to keep the intensity and distribution constant and vary the quality, or to keep the quality and distribution constant and vary the intensity. We hope in addition, to supplement this work by testing the eyes of employees who work under a given lighting system for several hours a day, for evidences of a progressive loss of efficiency.

IV. A PRELIMINARY STUDY OF THE CAUSES OF DISCOMFORT.

In addition to studying the conditions that give us maximal efficiency, it is important to determine the lighting conditions and eye factors that cause discomfort. In fact, it might well be said that our problem in lighting at present is not so much how to see better as it is how to see with more comfort and with less damage to the general health on account of eye strain. Any comparative study of the conditions producing discomfort necessitates a means of estimating discomfort. It is obvious that the core of the experience of discomfort is either a sensation or a complex of sensations. As such, it should have a limen or threshold value just as other sensations have; and just as we are able in general to estimate sensitivity in terms of the threshold value, so should we in this case be able to use the threshold

value in estimating the eye's sensitivity or liability to discomfort under a given lighting condition. Threshold values are usually determined by finding how much energy or intensity of a given stimulus applied for a short interval of time is required to arouse a just noticeable sensation. This form of procedure, however, is not adapted to the needs of our problem. It is much better to reverse the process and find how long the eye has to be exposed to a stimulus of a given intensity to arouse just noticeable discomfort. Our limen, then, becomes a time limen, and is measured in units of time instead of in units of intensity. In order to determine whether the judgment of the limen of discomfort can be made with certainty and to test in general the feasibility of the method, the writer undertook to determine the comparative sensitivity of the eye to discomfort when the source of light was exposed in different parts of the field of vision. In order to carry out this investigation, a 16 candle-power lamp was attached to the arm of a perimeter in such a way that the end of the bulb was always directed towards the observer's eye. The arm of the perimeter could be shifted to any meridian in which it was desired to work, and the lamp could be moved at will along the arm. It was thus possible to expose the light at any point in the field of vision that was desired. Working in this way, we have investigated the effect of many types of variation of the distribution of the light in the visual field, and it is our purpose to extend the investigation as fast as possible to the variation of the other factors. Of the variations we have made in the distribution of the light in the field of vision, it will be necessary, however, in order to illustrate the general method of working, to describe only one, namely, the exposure of the source of light at different points in the field of vision for one eye when fixation and accommodation were taken for a far point.

In carrying out the investigation, the following precautions were observed. (a) It was found better to work in a room moderately illuminated by a source of light behind the observer and entirely concealed from him rather than in the dark. The intervals of dark-adaptation between exposures in the dark-room seemed to make the observer's eye too sensitive for our purpose. This was especially true for certain parts of the peripheral retina.

In becoming supersensitive there was a tendency to become erratically sensitive. (b) It was found that blinking serves as a variable factor for the relief of discomfort and that the amount of blinking must be made constant from test to test. This was accomplished by having the observer blink at equal intervals during the exposure, timing himself by the stroke of a metronome. The interval most natural and suitable for this purpose was determined for each observer separately. (c) All comparisons were planned in series. For example, if it were desired to compare the sensitivity of the temporal and nasal halves of the retina in a given meridian, the exposure was first made at a given point in one half and next at the corresponding point in the other half. This was to guarantee that the eye should be as nearly in the same condition with regard to progressive fatigue, etc., as was possible. Further to safeguard against error in this regard series were compared in which the exposures were repeated in the reverse order. (d) An interval of recovery was allowed between exposures. This interval had to be determined separately for each observer and often had to be made different for the same observer on different days. It was never changed, however, during the course of an experiment, the results of which were to be compared. (e) In order that the observer's head be held rigidly in position during the exposure, he was required to bite an impression of his teeth previously made and hardened in wax on a mouthboard. When an exposure was to be made, the fixation was taken, the light turned on, and a signal was given by the observer when a just noticeable discomfort was aroused, or, if it was desired, when the different stages of discomfort were reached. The judgment was found to present no especial difficulty, and the method, when properly applied, to provide a feasible means for comparing the sensitivity of the eye to discomfort under all the conditions to which we have been able thus far to .extend its application. In actual practise the method also brings out an analysis of discomfort.

Discomfort seems to be a complex of three experiences, each of which develops at a different time. When the light is turned on, we have at once glare. This is a light sensation and though unpleasant has no painful elements. Next comes a conjunctival sensation

which begins with what is commonly called "sandiness" and soon passes over into a sharp, stinging, stabbing pain. Lastly there comes what is probably a muscular discomfort,—a hurting and aching in the ball of the eye which if the exposure is continued long enough seems to radiate to the socket and the surrounding regions of the face and head, the arch of the brow, the forehead, the temples, etc. Details will not be given here of the comparative sensitivity of different points of the retina to discomfort. It will be sufficient to say, that the periphery of the retina is more sensitive than the center; that the nasal half is in general more sensitive than the temporal half and the upper half than the lower half; and that in passing from the center to the periphery of the retina, the sensitivity is found first to increase then to decrease, becoming extremely little at the limits of the field of vision. In the horizontal meridians both on the temporal and nasal sides, maximal sensitivity is found around the 45 deg. point. In the vertical meridians, maximal sensitivity seems to be near the point 15 deg. below the horizontal. In a paper soon to be published, a detailed statement and explanation of these results will be given.

DISCUSSION.

DR. H. E. IVES: This paper is well worth the while of professional psychologists to study; and it gives to the illuminating engineer results which are extremely valuable.

When the illuminating engineer has the problem of producing satisfactory results, he has two methods of doing so; first, the case system, in which he copies an illumination produced by nature or invention, which has proved satisfactory by experience; and he hopes to get the same result. But there are defects in this method; we are very apt to follow the example of the Chinese who made motors by copying the imported ones even down to the color of the paint on the casings and the scratches on the paint We may do equally foolish things by slavish copying. That is inherent in the case system. Up to recently some of us have been of the opinion that even with the defects of this case system we could apply it to advantage, for instance by studying how nature produces her lighting schemes. But in order to make any great

progress we must deviate from what exists; we must experiment and invent. This necessitates some means of testing our results and this process of experiment and test constitute the second procedure. Our Society has lately been interested in the physiological side of illumination, but has been sadly handicapped by the lack of significant tests—we have been dependent practically on laboriously acquired experience. One great object in adopting a method of measurement is the saving of time. For instance, suppose our only means of measuring voltage was by the duration of physiological disturbances following an electric shock. In order to duplicate a voltage which gives a shock whose after effects last a day, we would require weeks or months of toil, because of the time necessary to wait for the results of each experiment. Suppose the first time we secured the desired voltage we had an instrument known as a "voltmeter;" it would only take a minute to determine that voltage. We want something for measuring the effect of lighting systems which will enable us to get results with a speed comparable with that of a voltmeter.

Various methods of test have been proposed and Dr. Ferree has gone over all of these. He arrives at a conclusion which I think it behooves us all to observe; namely, that these tests will show what he calls "the general level or scale of visual efficiency," but they are practically useless as tests of the *loss* of visual efficiency.

Here is a sentence which means a great deal "Just as a runner may, under the spur of his will, equal in the last lap of his course the highest speed he has attained at any other point in the course, so may the flagging muscles of the eye be whipped up to their normal power long enough to make the judgment required by the visual acuity test."

Dr. Ferree here gives us the benefit of his point of view and experience in these matters. In this paper he has recognized the inefficiency of the methods now used. He realizes that we want a test of the *loss* of visual efficiency. The eye may respond momentarily, like the tired runner, and see the object as distinctly as before, but we know that it is not as efficient. Dr. Ferree has devised a test in which is introduced a time element. The observer views a visual acuity test object. When the

limit of visibility is found the observer is not allowed to rest, because he will again after an interval get just as good results as at first; instead he presses a key as long as the detail is clear; then when the tired muscles flag and the object blurs, the finger on the key is removed. At first it appears easy to see the detail clearly, but pretty soon it is not so easy and one does not distinguish the chart so well. Very soon it becomes necessary to take the finger off the key. Intervals of clear and blurred vision alternate and at the end we have a ratio of the time the chart is distinguishable to the time when it is not.

Dr. Ferree has tried out daylight and a direct artificial lighting system and we have here for the first time the results of that test. They show what many of us have been sure of; that daylight does not decrease the efficiency nearly as much as artificial lighting. On the fourteenth and fifteenth pages are two charts showing by straight lines the falling off in efficiency which occurs under artificial lighting as compared to daylight. Personally, I think we should say "Eureka!"

I hope Dr. Ferree will proceed to standardize these tests and tell us the best working distances and one thing and another. As he is not here, I have tried to bring out the most important points. He has given us a most valuable contribution, and I hope before long we will be in a position to settle these questions of light and dark walls by this method of test and not by "Kilkennycat" discussion, which brings us nowhere.

I think we should do our best to aid Dr. Ferree to develop this method of test to give us what now we can get only by experience. I am aware that I have not done this paper justice, but I want to express my appreciation of his work.

Mr. C. O. Bond: The American Medical Association is a body whose conclusions as to the harmful or beneficial effects of any types of illuminating installations will carry considerable weight. They have discussed time after time how they were to make the tests, and this paper has grown out of Dr. Ferree's experiments, in the hope of placing in the hands of that Committee means of making the tests. We are extremely fortunate in having the first public report of this method. The method is under advisement by the Committee and I was present at one of their meetings when Dr. Ferree brought a set of this apparatus

to Philadelphia and they made a test of it. Two or three of the doctors present were very much impressed with it. I think, even if it does not succeed as it now stands, perhaps here is the germ of the best possible method of test.

Dr. C. E. Ferree (communicated in reply): I can express only great appreciation of the interest that the men who have preceded me have taken in our work. The problem is extremely interesting to me and I hope we have here a vulnerable point of attack. Once we have procured a successful method of measuring the effect of different lighting systems on the eye, a broad field of application opens out before us. We not only can find out what are the favorable and what are the unfavorable features in a lighting system, but we can no doubt, as may be inferred from Dr. Ives' discussion, test out and perfect a lighting system, so far as its effect on the eye is concerned, before we put it on the market. This latter point is a good one, I think, and I thank Dr. Ives for the suggestion.* I feel that Dr. Ives' perspective and practical grasp of the situation is a distinct contribution to the paper.

We are very much handicapped at present for funds by means of which to carry on this work. In the first place apparatus and models of lighting systems are required for the work on the laboratory side. Trained assistants are also needed to help out with the details of the work. Further, to verify and enlarge the work done in miniature in the laboratory, we should test the eyes of employees working under established lighting systems and in the surroundings in which these systems have to operate. All of this takes time and money, also entrance into commercial concerns. In all of these regards we need the help and influence of the Illuminating Engineering Society.

This work, I suppose, could be done spontaneously and sporadically here and there as the insight and inclination of various men may direct. But in the beginning, at least, I do not think it should be scattered. Until launched and safely moving, it should be done under common supervison.

* The general idea that over and above its application to abstract investigation the test may have an application in the daily work of the lighting engineer has come to the writer by suggestion from the engineers themselves. Mr. Cravath, for example, has recently pointed out that the test should be of advantage in making the actual installation of a lighting system. The writer would suggest in addition that it may further be of service in determining the effect of different kinds of type and paper on the efficiency of the eye; also the effect of different kinds of desk lighting, etc. In short, it is obvious that the usefulness of such a test is limited along these lines only by its sensitivity.

THE FACTORS THAT INFLUENCE THE SENSITIVITY OF THE RETINA TO COLOR:

A QUANTITATIVE STUDY AND METHODS OF STANDARDIZING

A Dissertation

PRESENTED TO THE FACULTY OF BRYN MAWR COLLEGE IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

BY

GERTRUDE RAND

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PREFACE.

The following study, practically as is here presented, was submitted to the Faculty of Bryn Mawr College in May 1911 in partial fulfillment of the requirements for the degree of Doctor of Philosophy. It is the outgrowth of a series of studies dealing with the phenomena of color vision that was begun in 1908 by the writer working under the direction of and in collaboration with Professor C. E. Ferree of Bryn Mawr College. In order to show in what way the present study, which deals with the formulation of a technique for investigating color sensitivity, is the logical outcome of the initial studies in the series, and is, moreover, required for the completion of the later studies, a brief résumé will be given of the work undertaken in the investigations preceding and following it.

The first of these studies entitled: *Colored After-image and Contrast Sensations from Stimuli in Which No Color Is Sensed,* was published in the *Psychological Review,* 1912, XIX, pp. 195-239. As is shown by the title, the article deals with the conditions under which colored after-image and contrast sensations may be aroused from stimuli in which no color is sensed. A formulation of these conditions, together with allied fusion and limen experiments, shows the phenomenon to be a peculiarity of the inhibitive action of brightness upon color. Brightness fused with color inhibits its saturation. With the exception of the region just within the limits of sensitivity for two colors, the following may be stated roughly as a law of this action for all colors and all parts of the retina: white inhibits most, grays in the order from light to dark next, and black least. This law was generalized from the results of fusion and limen experiments in a large number of meridians of the retina. In accord with this law, color may be obtained in the after-image when none is sensed in the stimulus when an unfavorable brightness quality is fused with the stimulus color and a favorable one with the after-image color. The technique for securing these conditions

for the after-image sensations in central and peripheral vision, for the contrast sensations in central vision, and for the phenomenon which we have called the Purkinje-Brücke phenomenon, is described in detail in the paper. But the study is not quantitative. The results do not show, for example, that the inhibition of the stimulus color has no effect upon the after-image. They show merely that, working near the limen, the stimulus color may be inhibited and the complementary color still be sensed in the after-image.

In order to determine as accurately as possible to what degree, if at all, the intensity of the after-image excitation is decreased by adding to the stimulus color a brightness excitation unfavorable to its saturation, the second study of the series was begun in 1909. It was entitled: *The Fusion of Colored with Colorless Light Sensation: The Physiological Level at Which the Action Takes Place.* An abstract of this article was published in the *Journal of Philosophy Psychology and Scientific Methods,* 1911, VIII, pp. 294-297. The full report will shortly be published in the *Psychological Review.* The results of this study have a twofold bearing. (1) They make plain once for all why it is possible to obtain color in the after-image when none is sensed in the stimulus, for they show that the intensity of the after-image excitation is not decreased at all by adding to the stimulus color a brightness excitation unfavorable to its saturation. (2) They throw some light on the broader problem presented by the fusion of brightness and color. By serving to indicate the level at which this action takes place, they help, for example, to explain a number of somewhat puzzling phenomena attendant upon the fusion of brightness with color, in case of positive, after-image, and contrast sensations. This action takes place apparently posterior to the seat of the after-image and contrast processes and the cancelling action of the complementary colors. There are two effects of the fusion of brightness with color, both of which are pressed into service in drawing the above conclusion: (1) it reduces the saturation of the color sensation; and (2) it changes the quality or tone of certain colors. This conclusion is based on the following lines of argument:

(1) When the color of the stimulus is inhibited by the addition of a brightness excitation, the intensity of the after-excitation, judged in terms of the duration of the after-image, is not affected by this excitation. (2) When the tone of the color aroused by a given stimulus is changed by the addition of a brightness excitation, the color of the after-image does not undergo a complementary change. (3) When the saturation of the inducing color is inhibited by the addition of a brightness excitation, the saturation of the contrast color is not affected by the change. (4) When the tone or quality of the inducing color is modified by adding a brightness excitation, the tone of the contrast color is not determined in the complementary direction. (5) When a given color is inhibited by the addition of a brightness excitation, its power to cancel the complementary color is not altered. (6) When the tone or quality of a color is altered by the addition of a brightness excitation, the tone or quality of the color required to cancel it is not affected by the change. (7) When the tone or quality of a color has been altered by the addition of a brightness excitation, the color component added can not be cancelled by mixing with the original color a color complementary to this component. Since, then, this fusion affects the positive and not the negative excitation and does not affect the cancelling action of the complementary colors, the conclusion is drawn that it takes place at some physiological level posterior to the seat of the after-image and contrast processes and to the cancelling action of the complementary colors. This study deals, however, only with the measure of the effect of the fusion of brightness and color as it occurs in central vision.

In order to extend the investigation to the peripheral retina, a third study was begun in June 1911. Its object was as follows. (1) It was planned to determine the effect of the fusion of brightness with color at a number of points from the center to the periphery of the retina, and to see how far the following points can be explained in terms of this action: (*a*) the influence upon the limits of color sensitivity of the brightness of the surrounding field and of the preëxposure; and (*b*) the color changes that occur in passing from central to peripheral vision. (2) A

comparative study was to have been made of the chromatic and achromatic phenomena of the peripheral retina. Both of these sets of phenomena for the peripheral retina show a number of striking differences from the phenomena of the central retina. Some of these points of difference are as follows: (*a*) There is considerable difference in the action of the achromatic qualities on color. (1) They inhibit or reduce the saturation of color much more strongly in the peripheral than in the central retina. (2) Of the achromatic qualities, white inhibits all colors the most strongly and black the least strongly in the central retina, while near the limits of sensitivity in the peripheral retina, black inhibits red and yellow the most strongly and white the least strongly. (3) The change in the tone or quality produced by adding white or black is much more pronounced in the peripheral retina and is often in a different direction. For example, black added to yellow in daylight illumination in the central retina turns it towards green; while in the peripheral retina the change is towards red. (*b*) Varying the brightness of the surrounding field has more effect on colors in the peripheral than in the central retina. (*c*) Exhaustion to color takes place more rapidly in the peripheral than in the central retina, that is, the change of saturation per unit of time is faster. (*d*) The colored after-image is of very short duration in the peripheral retina, but in proportion to its duration, it is much more saturated than the after-image of the central retina. (*e*) Some of the differences with regard to the achromatic phenomena are as follows. There is a very strongly increased sensitivity to contrast and to flicker; adaptation or exhaustion occurs very rapidly; the after-image is quickly aroused, is relatively very intensive, and in proportion to its intensity lasts a very short time; and so on. These points of difference raise the question how far we need go in assuming a different mechanism for the two parts of the retina. The purpose of our investigation was to have been primarily to determine how many of these differences are due at least in part to the difference in the state of brightness adaptation of the central and of the peripheral retina. (3) Maps were to have been made showing the sensitivity of the eye to the different

colors for three kinds of background (white, black, and gray of the brightness of the stimulus color). These three backgrounds were selected because they represent the extreme situations with regard to achromatic induction: maximal black induction, maximal white induction, and no induction; and, therefore, represent the best conditions that can be obtained for the study of the effect of the brightness of the surrounding field upon the local sensitivity of the retina. A sufficient number of meridians were to have been worked over to give an accurate outline of the zones of sensitivity for the three kinds of background used. Gradients were to have been established showing the falling off in sensitivity from the fovea outwards. Also the changes in color tone were to have been determined from point to point for all the backgrounds. Both sets of determinations were to have been made by matching in central vision what is seen in peripheral vision. The object of this investigation was to have been to give a complete representation of the sensitivity of the entire retina, quantitative and qualitative, in terms that are more or less familiar to all, namely, the sensation values of the central retina. It was found, however, that the large M. V. occurring in the work from observation to observation rendered the extended comparative investigation planned impossible. The original plan had, therefore, for the time to be abandoned, and the present study was undertaken.

This study aims (1) to determine what are the factors that influence the sensitivity of the retina to color; (2) to make a quantitative examination of the factors extraneous to the stimulus; and (3) to provide methods for their standardization. For the sake of historical continuity, the study is preceded by an historical and critical résumé of the analyses of factors influencing color sensitivity that have been made up to this time and of the attempts to standardize. It may be stated in passing that with the control of factors rendered possible by this study, the original plan of work has been resumed and in part completed. It will be published in the near future.

There remains to be mentioned the relation of the present study to the final one of the series. The latter has developed

from the historical and critical résumé mentioned above of the investigations that have been made to determine the factors that influence the sensitivity of the retina to color. In the course of this discussion various deficiencies have been pointed out in the methods used by previous investigators in their attempts to control these factors, and ways have been devised to correct these deficiencies. The factors that influence the sensitivity of the retina to color may be divided into two classes: those pertaining to the stimulus, and those extraneous to the stimulus. The experimental part of the present study is especially directed toward making a quantitative estimate of the latter set of factors under various typical conditions obtaining in the investigation of color sensitivity and toward securing effective methods of control. No concern is had, however, to standardize the factors pertaining to the stimulus any farther than is necessary to accomplish this purpose. The more effective standardization of these factors will form the subject of our future work. The question of intensity will be taken up first. It has been shown in the historical part of the present study that this factor has been most inadequately handled by previous investigators. In determining the comparative sensitivity of the retina to the different colors, for example, either no account has been taken of the different intensities of the colors used, or incorrect methods have been employed of equalizing these intensities. In no case has the determination been made in terms of units that can be compared. It is the writer's purpose to make an exhaustive determination of the sensitivity of the retina to the different colors in terms of such units. The comparative limits of sensitivity will be determined in a number of meridians with stimuli equalized in energy, and the limens and the j.n.d's. of sensitivity at different degrees of intensity will be determined in terms of radiometric units at various points from the center to the periphery of the retina in the different meridians. This investigation in fact is now in progress. A preliminary statement of the plan of this work has already been published by the writer in collaboration with Professor Ferree (American Journal of Psychology, 1912, XXIII, pp. 328-332).

From the above discussion of the place of the present study in the series, it will be evident to the reader how extensively this study has been due to the instruction, guidance, advice, and assistance of Professor Ferree, and how great a debt of gratitude the writer owes him. In stating his share and collaboration in the studies preceding and following this in the series, I can indicate perhaps more fully than in any other way the share he has had both directly and indirectly in the production of the present study.

I. INTRODUCTION.

In no branch of psychological optics does one find such varied and contradictory results as in the work on the color sensitivity of the peripheral retina. This is doubtless due in minor part to the intrinsic difficulty of the indirect vision observation, but in major part it is due to the lack of adequate standardization of the factors that influence the local stnsitivity of the peripheral retina. These factors may be divided into two classes: (*a*) those pertaining to the stimulus, or the source of light; and (*b*) those extraneous to the source of light. In the former class may be included the size, intensity, and brightness of the stimulus; in the latter, the preëxposure or what the eye has rested on before being exposed to the stimulus, the surrounding field, and the general illumination of the visual field.[1] The work of standardization thus far has been directed largely towards the factors in the former class. Of the factors in the latter class, attempts have been made, as will be shown later in the discussion, to standardize only the influence of surrounding field. The recognition of the importance of this factor came relatively late in the development of the technique of the subject. It was at one time thought that the use of the perimeter and the dark-room provided ideal conditions for testing the local sensitivity of the peripheral retina, because by this means the local area alone was stimulated by light, hence it was thought that the influence of the surrounding field was eliminated. We know now that these conditions were not so ideal as they seemed, that a dark- as well as a light-

[1] In case the colored light is obtained by reflection from a pigment surface, some exception may be taken to the above classification, for unless some especial device be used to illuminate the pigment surface, the intensity of the stimulus will depend upon the degree of the general illumination of the visual field, and the brightness of the stimulus will also, to a certain extent, be dependent upon the general illumination. In such a case, these factors would have to be included in both classes. If on the other hand the colored light is obtained by means of standard filters, or from the spectrum, the illumination of the visual field will exercise its influence entirely independently of any effect on the stimulus.

adapted retina influences by contrast the sensitivity of the area stimulated. The use of the perimeter and dark-room accomplishes, then, but a very small part of the purpose for which it was intended. Instead of eliminating altogether the influence of the brightness of the surrounding field, it makes only one phase of it constant. It standardizes by giving us one state of brightness-adaptation alone, namely, the adaptation of the dark-room.[2] The campimeter was devised especially to correct this deficiency. Its purpose is to control and standardize the influence of the brightness of the surrounding field when one is working with a light-adapted retina. But the campimeter, like the perimeter, has accomplished only in part the purpose for which it was intended. It standardizes the influence of the surrounding field for one degree of illumination only, because the influence of the campimeter screen changes markedly with changes in the illumination of the visual field. There are two reasons for this. (*a*) A brightness match between the colored stimulus and the gray of the surrounding field made at one illumination will not hold at another. And (*b*) the sensitivity of the retina to brightness induction changes markedly with changes in the general illumination. This latter point is especially true in the peripheral retina where changes which are too small to be detectable by any current photometric device produce quite a noticeable change in the amount of induction between two surfaces of different brightness. The campimeter, then, is almost useless as an instrument of precision, unless the general illumination can be rendered constant or some means can be devised for standardizing the observation for changes of illumination. No satisfactory method has as yet been obtained for keeping the illumination of a room by daylight constant. To keep it constant presupposes what has not as yet been provided, namely, a sensitive means of measurement. Constancy may be approximated by artificial illumination,

[2] As will be shown later in the paper, neither the influence of surrounding field nor of preëxposure can be eliminated when the observation is made in the dark-room. The influence of these two factors can be eliminated only by working in a light-room of constant intensity of illumination, and by using a preëxposure and a surrounding field of the brightness of the color used for the stimulus.

but no artificial source has yet been devised which gives a light that approaches average daylight[3] sufficiently closely in composition to warrant its use in color work. Of the various sources of light the Moore Tube comes nearest to doing this, but spectrophotometric and colorimetric determinations show that the light from it contains an excess of blue[4] and, therefore, although it has been adopted by various textile concerns for use in color matching, its substitution for daylight can scarcely be recommended for the more exact requirements of color optics. Ives and Luckiesh[5] attack the problem of producing artificial daylight from another side. By their subtraction method they claim to have gotten the closest approximation to average daylight yet attained. They aim to cut out by absorbing screens the excess of red and yellow in artificial light due to the comparatively low temperature of artificial illuminants. Tungsten lamps are used by them as the source of light, and two kinds of commercial glass approximating in their absorptive action cobalt blue and signal green are used as screens. In order to correct for the pronounced band of yellow-green transmitted by the cobalt blue, a film of gelatine dyed with rozazeine is also used. Although according to comparative measurements made by Ives and Luckiesh the light thus gotten is the closest approximation to average daylight yet obtained, still it shows a deficiency of 15% in the green and about 25% in the blue. Moreover, the spectrum of this light does not show the brightness distribution of the spectrum of daylight. Since the absorbing screens cut down the light emitted by the tungsten lamp to 15% of its original intensity, the spectrum of

[3] For results of measurements of the color values of average daylight, see Nichols, E. L. *Transactions of the Illuminating Engineering Society,* 1908, III, p. 301. Ives, H. E. The Daylight Efficiency of Artificial Illuminants. *Transactions of the Illuminating Engineering Society,* 1909, IV, pp. 434-442; Color Measurements of Illuminants. *Transactions of the Illuminating Engineering Society,* 1910, V, pp. 189-207.

[4] See Ives, H. E. Color Measurements of Illuminants. *Transactions of the Illuminating Engineering Society,* 1910, V, p. 206; and Rosa, E. B., quoted by Moore, D. McF. A Standard for Color Values. *Transactions of the Illuminating Engineering Society,* 1910, IV, p. 224.

[5] Ives, H. E. and Luckiesh, M. Subtractive Production of Artificial Daylight. *Electrical World,* 1911, LVII., pp. 1092-1094.

the light finally given out shows the brightness distribution characteristic of lights of low intensity, unless the original light-source is of extremely high candle-power.

We seem thus compelled either to give up the investigation of the sensitivity of the retina for daylight illumination, or to devise some means of keeping this illumination constant. At an early stage in the study of the color phenomena of the peripheral retina begun four years ago and still in progress in the Bryn Mawr Laboratory, the writer was compelled to take into account the influence of the changes in the illumination of the visual field upon the color observation. The changes of illumination that took place from day to day, the progressive changes during the day, and the many sudden changes even in the course of an hour, rendered any constancy, or close reproduction of results entirely out of the question. The consideration of this factor led in turn to a general study of the conditions that influence the color observation. It is the purpose of this paper to report the results of that study. The report will take the following form.

(1) A résumé and criticism will be given of previous studies of factors, and of attempts to standardize. (2) The color observation will be reexamined for the factors that influence its results, and a study of these factors will be made with the following points in view: (*a*) Their influence will be measured under various typical conditions obtaining in the work on color sensitivity. (*b*) Their effect on the limen of color at different points in the retina and on the limits of color sensitivity will be determined. (*c*) An explanation based on the conclusions drawn from (*a*) and (*b*) will be made of the results of other experimenters and of the contradictions found in these results. (3) From this study of the influence of the factors, it will be determined what factors need to be standardized in the various kinds of work on color sensitivity and methods will be devised for their standardization.

In the latter part of the work especial attention will be given to the effect of general illumination and of local preëxposure. The writer finds these to be the two most important factors extraneous to the source of light that influence the results of the color obser-

vation, and yet, so far as she is able to determine, up to this time no attempt worthy of more than passing consideration has been made to standardize either factor in investigations of color sensitivity. In fact, it can scarcely be said that either has been included in the list of factors by any previous writer. The effect of the general illumination has received only casual mention by Ole Bull and a few others, and the brightness of the preëxposure has not been clearly recognized as exerting any influence whatever.

II. HISTORICAL AND CRITICAL.

A. FACTORS THAT HAVE BEEN FOUND TO INFLUENCE THE SENSITIVITY OF THE RETINA TO COLOR.

1. *Size of the Stimulus.*

An increase in the size of the stimulus is generally considered to be equivalent in some proportion to an increase in intensity.[1] It is but natural, then, to think that an increase in the size of the stimulus would both lower the limen of sensitivity and extend the limit of the zone within which a given color can be sensed. The question with regard to the limits of sensitivity is, however, not so simple as it seems. In the first place, the limit of the zone may not be extended, because the retinal sensitivity may fall off so rapidly at the point worked upon, that the increase of stimulation is not sufficient to overweigh the loss. In the second place, the effect of the increase of area may depend to some extent upon the area of the original stimulus. For example, fatigue is set up so easily with very small stimuli that an increase up to a certain point is advantageous, while, on the other hand, the outer margin of large stimuli may extend so far into the zone of relative insensitivity that a further increase of area becomes ineffective. In the third place, the effect may vary with the meridian of the retina investigated. Two reasons may be assigned for this variation. (*a*) We should expect the effect to be in some measure proportional to the rapidity with which the retina falls off in sensitivity from the fovea to the periphery. For example, in the temporal and lower

[1] Raehlmann, E. Ueber Farbenempfindung in den peripherischen Netzhautpartien in Bezug auf normale und pathologische Brechungszustände. Inaug. Diss., Halle, 1872.

While the work of Raehlmann and others shows in general the truth of the above statement, no systematic determination of the exact relation of change of area to change of intensity has yet been made. This determination for the sensations aroused both by white and colored light is now in progress in the Bryn Mawr laboratory.

meridians, where the sensitivity falls off sharply, we should expect little if any effect; while in the nasal and upper regions, where the decrease is much more gradual, we should expect considerable effect. (*b*) In the nasal and upper meridians, the limits of sensitivity extend much farther toward the periphery than in the temporal and lower meridians. There is in these meridians, then, as the limits of sensitivity are approached, a relatively greater shrinkage in one dimension of the stimulus, owing to the greater angle of excentricity, than occurs in the temporal and lower regions. In proportion as this shrinkage causes a shortening of one dimension of the stimulus, it adds to the range of areas over which an increase is of advantage for extending the limit of sensitivity.

A survey of the literature on peripheral vision shows that the size of the stimulus was early recognized as one of the factors influencing the sensitivity of the peripheral retina. In fact, the first investigation of peripheral sensitivity was made to determine the effect of the size of the stimulus. This work done by Hueck[2] in 1840, may be considered as pioneer, for although Troxler[3] and Purkinje[4] had previously mentioned the phenomena of peripheral vision, they had made no systematic attempt to investigate these phenomena. Hueck's object was primarily to study the effect of increase in the size of the stimulus upon the limits of the field of vision. Using gray paper stimuli of very small area, he observed the effect on the limit of vision (*a*) when their objective size was increased, and (*b*) when their apparent size was altered by a decrease in their distance from the observer, that is, by enlargement of the visual angle. He found that an increase in size produced in either of these ways caused a widening of the field of vision for that quality of stimulus. The investigation was also extended to color. Pig-

[2] Hueck, A. Von den Grenzen des Sehensvermögens. Müller's Archiv, 1840, p. 95.

[3] Troxler, D. Ueber das Verschwinden gegebener Gegenstände innerhalb unseres Gesichtskreises. Ophthal. Bibliothek herausgegeben von Himly u. Schmidt, Jena, 1804, I, 2. pp. 1-53.

[4] Purkinje, J. Beiträge zur Kenntniss des Sehens. 1823, I, p. 76; 1825, II, p. 14.

ment papers were used. This investigation showed that the limits of color sensitivity also are influenced by the size of the stimulus. An interesting table was compiled which shows that by altering either the size of the stimulus or the visual angle it subtends, the limit of sensitivity can be made to vary by amounts equal to 1° over a wide range of the retina. Hueck's conclusion, that the limits of color vision are influenced by the size of stimulus, was confirmed by Aubert[5] in 1865. Five years later it was contradicted by Woinow.[6] Woinow worked in the dark-room, using for stimuli colored glasses illuminated by a shaft of sunlight of variable extent. He claimed that "die Grenze immer dieselbe ist, ohne Rücksicht auf die Grösse der Pigmentfläche, wenn die Gesichtswinkel nicht von der Mitte sondern von dem dem Auge zugekehrten Rande der Pigmentfläche berechnet werden." No information is given as to the size of stimuli employed. Krükow,[7] repeating Woinow's precaution of measuring the angular distance to the inner edge of the stimulus rather than to the middle, confirmed the conclusion that the boundaries of the color zones are absolute, within certain limits of size of stimulus. His stimuli were 3, 6, and 9 mm. square. Aubert[8] in 1876, repeated the observations recorded in his earlier work. Colored squares with sides varying from 1 mm. to 32 mm. placed at a distance of 20 cm. from the eye were used as stimuli. The results he obtained led him to believe that the size of the stimulus is a factor in determining the limits of sensitivity. He writes: "Die Grösse des farbigen Objectes massgebend ist für die Entfernung vom Centrum, in welcher es noch farbig empfunden wird. Die gegentheilige Behauptung Woinow's . . . muss ich nach vielfacher, wiederholter Untersuchung für falsch erklären." He mentions the precaution used by Woinow as to the measurement of the angular distance, but does not definitely state that he himself took this precaution. Raehl-

[5] Aubert, H. Physiologie der Netzhaut. Breslau, 1865, p. 121.

[6] Woinow, M. Zur Farbenempfindung. A. f. O., 1870, XVI, p. 219.

[7] Krükow. Objective Farbenempfindung auf den peripherischen Theilen der Nezhaut. A. f. O., 1874, $XX_{,1}$, pp. 255-296.

[8] Aubert, H. Physiologische Optik. Leipzig, 1876, pp. 541-544.

mann,[9] Schön,[10] Schirmer,[11] and Briesewitz,[12] all agree with Aubert; but they also have not mentioned their method of measurement.

In Tschermak,[13] however, we find an investigator who has observed Woinow's precaution and yet has obtained results that are contradictory to Woinow's. He investigated the factors which condition the colorless vision of the peripheral retina, and showed that neither the red-green nor the totally color-blind zones of the normal retina are invariable in extent. Size of stimulus was found by him to be one of the factors that determine the breadth of these zones. This he demonstrated on the Hering apparatus for investigating the color sensitivity of the peripheral retina, an apparatus consisting of a campimeter screen with an opening behind which the stimulus is placed. Tschermak's screen was of gray paper. The size of the stimulus-opening was regulated by means of two gray slides which widened the opening either on the side within the visual field and toward the fovea, or on the other side toward the periphery. Using a small stimulus-opening, he determined the degree of excentricity at which *Urgrün* and *Urroth* appeared colorless. He then widened the stimulus-opening toward the fovea and found that the color was sensed. No conclusion, however, can be drawn from this because he had extended the inner margin of the stimulus into the region sensitive to color, hence the sensation aroused may have been due to that cause rather than to the increase made in the area of the stimulus. He next widened the original stimulus-opening toward the periphery. This caused an increase in the area of the retina stimulated, without extending the margin of the stimulus into the field sensitive to color. Since in this case also the color was sensed, Tschermak concludes that the

[9] Raehlmann, E. loc. cit.

[10] Schön, W. Ueber die Grenzen der Farbenempfindung in pathologischen Fällen. Klinische Monatsblätter, 1873, p. 171.

[11] Schirmer, R. Ueber erworbene and angeborene Anomalien des Farbensinns. A. f. O., 1873, XIX, p. 194.

[12] Briesewitz. Ueber das Farbensehen bei normalem and atropishem Nervus Opticus. Inaug. Diss., Greifswald, 1873.

[13] Tschermak, A. Beobachtungen über die relative Farbenblindheit in indirectem Sehen. Pflüger's Archiv, 1890, LXXXII, pp. 559-560.

limits of color sensitivity are influenced by the area of the stimulus. It is in the second method of increasing the area of the stimulus that Tschermak took the precaution mentioned by Woinow relative to the measurement of the angle of excentricity.

But it is obvious that the method of measurement need not have been the only cause of variable results in work of this kind. The meridian tested may have been, as we have already suggested, a second cause. That certain regions of the retina react differently to an increase in the area of the stimulus, is noted in a brief paragraph by Kirschmann.[14] Using stimuli of 28, 40, and 58 mm. in diameter, he found that the color sensitivity of the peripheral retina is dependent to different degrees in different meridians upon the size of the stimulus. In the lower and temporal meridians, the zone sensitive to each color was widened very slightly by increasing the area of the stimulus, and never beyond certain limits. On the upper and nasal parts of the retina, however, the possibility of widening the zones by this means seemed to be, he says, unlimited. Now we know that Woinow and Krükow obtained their results on the temporal meridian. Tschermak, however, does not state what region he investigated. If he worked in the nasal region, his conclusions may be reconciled with those of Woinow in the light of Kirschmann's work. These variations in the effect of area in different regions of the retina are no doubt due largely to the difference in the rapidity with which sensitivity falls off from the center to the periphery of the retina along the several meridians. Where the decrease is gradual, as is the case in meridians that have wide limits of sensitivity, more effect might be expected than where the sensitivity decreases rapidly.

A third cause of the variable results recorded may have been the range of size of stimuli employed. The retina fatigues easily to very small stimuli; hence an increase in size up to a certain point is advantageous. On the other hand, the margins of very large stimuli may extend so far into the zone of insensitivity that a further increase is ineffective. Krükow no doubt

[14] Kirschmann. A. Die Farbenempfindung bei indirectem Sehen. Philos. Studien, 1893, VIII, p. 612, 613.

referred to this fact when he said that color sensation is independent of the size of the stimulus, but only within certain limits. An interesting conclusion reached by Abney[15] may also be mentioned in this connection. He wished to determine at what intensity the different colored spectral lights were brought below the limen of sensation both in central and at various points in peripheral vision. He found, however, that the intensity of the stimulus is not the only factor to be considered. A stimulus 2 inches in diameter, for example, was seen at a lesser intensity than a stimulus ½ inch in diameter. He further found that it is not the area, but the shortest dimension of the stimulus, vertical or horizontal, which determines the intensity required to render the stimulus subliminal.

The following table has been compiled from the results of his work in central vision.

Stimulus		*Relative Intensity*	*Value of Light*
disc	.95 in. diameter	234	97.4
square	.84 in. x .84 in.	216	139.2
rectangle	1.68 in. x .42	152	495.2
square	.84 in. x .42	154	478.4

The areas of the disc, the square, and the first rectangle are equal, but the rectangle which has the shortest dimension, requires 400 units more of light intensity than does the disc in order to be made just subliminal. The fourth stimulus has half the area of the third, but their shortest dimensions are equal, and accordingly the same amount of light is required to render them both just subliminal. The experiments were extended by Abney to the peripheral retina, and the conclusion was again reached that the shortest dimension of the stimulus and not its area determines the reduction in intensity necessary to render the stimulus just subliminal (p. 183). Since Abney found further that "there is a simple connection [relation] between the intensity of the stimulus color and the extent of the color field," we may infer that he would have us conclude that the extent of the color field is also influenced by the shortest dimension of the stimulus.'

The present status of this point may be summarized as follows:

[15] Abney W. de W. The Sensitiveness of the Retina to Light and Colour. Philos. Trans., 1897, CXC, Ser. A, pp. 169-171.

Within a certain range of dimensions and particularly for certain regions of the retina, the size of the stimulus is an important factor in determining the extent of the color zones. And with regard to size, the shortest dimension of the stimulus and not its area is, according to Abney, the determining factor. Care must be taken, therefore, to measure accurately the size of the stimulus used in peripheral investigation, also its distance from the observer, and to keep these measurements uniform throughout the investigation.

2. *Intensity and Brightness or White-Value of the Stimulus.*
(*a*) *The confusion that has arisen with regard to the meaning of intensity and of brightness, and its effect upon the development of methods of working.*

Before we attempt to discuss the influence of the intensity and the brightness of the stimulus upon the limits of color sensitivity, some attention should be given to a definition of terms. The need for this will be shown by a brief examination of the literature on these subjects. A great deal of confusion as to terminology seems to exist, and not a little misinterpretation of fact seems traceable to this confusion. The greater part of the confusion arises from the use of the word *intensity*. This term has been employed at various times to indicate (*a*) the energy of a beam of spectral light homogeneous as to color; (*b*) the white-value of a color; (*c*) the saturation of a color; and (*d*) the energy of light-waves reflected from a pigment surface as conditioned by the general illumination of the visual field. This equivocal use of the term has now and then apparently led to a wrong interpretation of results, and this in turn to the modification of experimental technique. An example of this is found in the work done by Baird in the Cornell laboratory on *"The Color Sensitivity of the Peripheral Retina."*[16] In his review of the literature, Baird finds data that lead him to assume that an equation of the white-values of the stimuli employed is essential for a determination of the relative extent of the retina's sensitivity to the different colors. Apparently these data are derived

[16] Baird, J. W. The Color Sensitivity of the Peripheral Retina. Carnegie Institution of Washington, 1905.

mainly from three sources: (*a*) from a study of the color sensitivity of the peripheral retina made by Aubert; (*b*) from a study by Abney of the effect of changes in the energy or intensity of spectral light upon sensation; and (*c*) from a study of the limits of color sensitivity made by Landolt.[17] An examination of the investigations made by these men shows, however, that Baird's conclusion is apparently based upon a loose construction put upon the meaning of certain terms. The most striking example of this, as we shall see, results from the interpretation given by Baird to the term *intensity*. Baird uses *intensity* to indicate *luminosity* and, as we shall show, he also uses *luminosity* interchangeably with *brightness* or *white-value*. Landolt and Abney, on the other hand, from the results of whose investigations of the effect of intensity on color sensitivity Baird largely draws his conclusions as to the need of equating the white-value of his stimuli, clearly use the term *intensity* to mean the *energy* of the light-waves coming to the eye.

According to Baird, the first mention of the need to equate in brightness was made by Aubert. Baird writes: "His [Aubert's] results may be summarized as follows:

"1. The brightness of the background has a most pronounced influence upon the extension both of the color sensitivity and of the brightness sensitivity.

"2. The extension of the color zones increases with increase of area of stimulus.

"3. The color sensitivity decreases at very different rates upon different retinal meridians.

[17] Baird claims to derive authority also from the work of Raehlmann, Klug, Chodin, Bull, Hess, and Hegg. We have considered that this authority is derived mainly from Aubert, Landolt, and Abney, however, because Baird discusses the results of these three men and to some extent their methods of working, giving several sentences to show that their work points out the need for equation of the white-values of the stimuli employed to investigate color limits. To the other men from whom he claims to derive authority, Baird devotes merely a sentence to each which states, in case of Raehlmann and Klug, that they had found that the color limits vary with changing brightness of stimulus; in case of Chodin, that he believed that brightness equation was necessary; in case of Bull, Hess, and Hegg, that they had equated the white-values of their stimuli. The discussion of these cases will be taken up later in the paper (see pp. 51-53).

"4. The transitions of color tone are as follows: Red passes through reddish-yellow and yellowish-gray to gray; green becomes yellowish, while yellow and blue undergo no change of tone, but decrease in saturation and finally appear gray.

"5. The relative extension of the color zones can not be determined with any degree of accuracy. Since the width of the color zone is a function of the luminosity of the stimulus, the color-stimuli employed in the determination of comparative retinal limits must all be equated in brightness.

"6. There is a close analogy between the functioning of the central and peripheral parts of the retina."[18]

Baird seems to derive his authority for the need to equate in brightness, so far as Aubert is concerned, from the fifth of these points of summary. From the wording of the text it is impossible to state the exact source of Baird's quotation since he bears himself out in his summary only by a general reference to a long list of Aubert's articles on vision.

But the organization of this summary is so closely akin to that given in the *Physiologische Optik,*—the only difference being in the omission by Baird of the third item in the *Optik* summary,—that one seems justified in asserting that this work contains the source of the statement quoted above. In no other of Aubert's articles are all of the points mentioned by Baird touched upon. The earlier articles are narrower in scope than the *Optik* and treat of fewer factors.

Aubert's statement of results in the *Physiologische Optik* is as follows: "Durch meine Versuche wurde festgestellt

"1. der grosse Einfluss welchen die Umgebung der Pigmente auf die Farbenempfindung auch beim indirecten Sehen hat.

"2. der Umstand, dass die Grösse des farbigen Objectes massgebend ist für die Entfernung vom Centrum, in welcher es noch farbig empfunden wird.

"3. dass Pigmente verschiedener Farbentöne unter sonst gleichen Umständen verschiedene Grenzzonen für die Erkennbarkeit der Farbe zeigen.

"4. dass in die verschiedenen Meridianen der Netzhaut die

[18] Baird, J. op. cit., pp. 12-13.

Grenzzonen für die Farben sehr verschieden weit von dem Fixationspunkte liegen.

"5. Schon Purkinje hat verschiedene Uebergänge durch Farbentöne und Farbennuäncen beobachtet, und zwar geht auf schwarzem Grunde nach Aubert: Roth durch Rothgelb und Gelbgrau zu Grau, Blau durch immer weisslichere Nuäncen zu Grau, Grün durch Graugelb zu Grau, Gelb durch Graugelb zu Grau.

"6. Donders und Landolt haben nachgewiesen, dass die Farbenempfindung auf den peripherischen Netzhautzonen eine dem Centrum gleiche bleibt, wenn die Intensität der Beleuchtung gesteigert wird: also auch beim indirecten Sehen sind Gesichtswinkel und Helligkeit massgebend für die Farbenperception.

"7. dass die peripherischen Theile der Netzhaut für die Farbenempfindung viel schneller ermüden, also die centralen."[19]

To Baird's fifth point of summary, the closest approximation that the writer is able to find anywhere in Aubert's works is the sixth conclusion quoted above from the *Optik*. This is: "Donders and Landolt haben nachgewiesen, dass die Farbenempfindung auf die peripherischen Netzhautzonen eine dem Centrum gleiche bleibt, wenn die Intensität der Beleuchtung gesteigert wird: also auch beim indirecten Sehen sind Gesichtswinkel und *Helligkeit massgebend für die Farbenperception.* Nagel bestätigt Landolt's Angabe."[20] The question here is whether *Helligkeit* in the above quotation means *brightness of stimulus* which, if our assumption with regard to the source of his authority is correct, Baird has apparently interpreted it to mean. The following points may be cited to show that such an interpretation is very strongly open to question. (*a*) Aubert himself does not use *Helligkeit* in connection with a qualifying phrase, for example, *Helligkeit der Farben* or its equivalent, while so far as the writer is able to determine, he never uses *Helligkeit* as referring to the *brightness of color* without the qualifying phrase. For example, in his Physiologische Optik p. 527 he uses Helligkeit der Farben; p. 528, Helligkeiten der verschiedenen Abtheilungen des Spectrums; p. 529, Helligkeiten der Farbentöne des Sonnenspectrums;

[19] Aubert, H. Physiologische Optik, Leipzig, 1876, pp. 541-545.
[20] Aubert, H. Physiologische Optik, Leipzig, 1876, p. 545.

same page, Helligkeiten der Farben; p. 530, Helligkeiten der Abtheilungen des Spectrums. In his Physiologie der Netzhaut p. 109 he uses, Helligkeit der Pigmente. The same expression is used again on pp. 111 and 112. (*b*) When using *Helligkeit* without a qualifying phrase, Aubert commonly refers to the *intensity* or *brightness of the general illumination.* For examples of this usage, see Physiologie der Netzhaut, pp. 109, 110, 124; Physiologische Optik, p. 532, and other places. (*c*) No evidence can be obtained from Landolt from whom the citation is made that brightness of color is referred to. In fact the evidence is strongly against this interpretation. As will be shown in detail (pp. 24-25), Landolt worked with colors of varying energy. He used as stimuli very intense spectral light and pigment papers. The energy of the former was varied directly, of the latter by changing the general illumination which altered the amount of colored light reflected to the eye. In the general statement of his problem Landolt is not concerned with the effect of the brightness of his colors; nor are his results couched in terms of the effect of the brightness of colors. His sole interest was to find the effect on sensation of using colors of great energy or intensity. In the above quotation from Aubert, then, we may conclude that it is strongly open to question whether *Helligkeit* is not also used here in the sense in which we have shown that Aubert most frequently uses the term: the brightness of the general illumination (see (*b*) above). If so, what he really does claim in this statement, therefore, is that when one is working with pigment colors, the degree or brightness of the general illumination with all of its influences, namely, its effect on the intensity of color, on the brightness of color, on the brightness of the surrounding field, the preëxposure, etc., is one of the factors that determine the extent of the color field; not simply one of these influences, the brightness of color, as he is interpreted to claim by Baird.[21] Moreover, the writer is compelled to say that in a careful reading of all the articles by Aubert contained

[21] For Aubert's own statement of his opinion on the question of the influence upon color sensitivity exerted by the brightness of the stimulus see this article, pp. 40-44.

in the long list to which Baird refers, she is unable to find a single statement that would justify the conclusion that Baird has drawn in his fifth point of summary.

Towards Landolt and Abney, Baird takes a slightly different attitude. He does not hold that they have mentioned a need to equate in brightness. In their results, however, he finds justification for equating the white-values of his own stimuli from the construction he puts upon their use of the words *luminosity* and *intensity*. Abney,[22] a physicist, had defined *luminosity* as equivalent to *intensity*. In his experiments he had increased or diminished the luminosity or, as he also says, the intensity of a beam of light by interposing in its path a wedge graduated in thickness. The wedge was made of gelatine in which were scattered black opaque particles. The energy of the beam of light was diminished by amounts depending on the thickness of that part of the wedge through which it was made to pass. This "obstruction method" resulted not only in a decrease of the energy of the light, but in a darkening of the stimulus. But Abney was not at all concerned with the effect of the lightness or darkness aspect of the stimulus:—in other words, with the relative inhibitive action of white and black and its influence on the limits of color sensitivity. His purpose was to vary the energy of the light-waves coming to the eye by "obstructing" them by known amounts, and to ascertain the effect of this change upon the color limits. It is true that the lightness or darkness of the sensation quality was altered incidentally, but he apparently had no thought of saying that this was in any sense responsible for the effect obtained, nor is it a necessary inference from his work. Hence Baird is not justified in stating (p. 31) that Abney makes the brightness of the stimulus a factor in determining the color limit, if we take our clue as to what Baird means by brightness from the following passage. "No determination of the relative extensions of the various color zones can ever yield comparative results unless it be accomplished by means of stimuli of equal brightness, or, more correctly speaking, of equal white-value" (see p. 37). For Abney assuredly, does not mean by *lum-*

[22] Abney, W. op. cit., 155-195.

inosity what Baird calls *brightness* or *white-value*. Baird falls into a similar error in his treatment of Landolt's results. He says: "An important feature of Landolt's paper is his insistence that no investigation of color vision is complete unless it takes into account the relative luminosity of the stimuli employed" (p. 17). Now when we read in a footnote (see Baird p. 34) that "Under brightness [of stimulus] is included both absolute and relative luminosity of stimulus, *i.e.*, its own brightness and its brightness contrast with its background," we see that the relative luminosity referred to by Landolt means for Baird relative brightness or white-value, and that the work of Landolt is brought forward as as evidence for the necessity of equating the white values of the stimuli. Now Landolt worked with both spectral and pigment stimuli. In case of the first, his method was to increase the energy of spectral light; and in case of the second, to increase the amount of light coming to the eye from a pigment surface by increasing the general illumination of the room. Here, as in the case of Abney, we have a change in the amount or energy of the colored light coming to the eye, and incidentally a change in the white-value of the sensation aroused. No separation is made, however, of the two factors: (*a*) the altered energy of the colored light, and (*b*) the change in the white-value of the sensation aroused. Yet Baird finds reason to conclude from Landolt's results that the white-value of the color influences the limits of sensitivity. It is obvious that Landolt's results do not show this at all. All that they do show is that when the amount of colored light given to the eye is increased or decreased, the extent of the zones of sensitivity is altered.[23]

Whether or not the white-value of the stimulus can be considered to any degree responsible for changes in the color limits

[23] These three cases taken from Baird's discussion of the work of Aubert, Abney, and Landolt are examples of the cases referred to earlier in the chapter in which a confusion as to terminology has led to a wrong interpretation of results which in turn has been the cause of changes in technique. Baird was led by this confusion, in part intrinsic and in part due to his own misinterpretations, to think that these three men considered that the white-value of the colored stimulus affects the extent of the retina's sensitivity to it, and was influenced thereby to equate the white-values of his stimuli without further investigation.

will be considered by the writer in the experimental section of this paper. What we wish to point out here is that without the isolation and the separate investigation of this factor, Baird concludes from the work of previous investigators in which intensity or energy changes have been made in the stimulus, that the white-value of the stimulus influences the boundaries of the color zones and that, therefore, stimuli should be equated in white-value in all work on the limits of color sensitivity. He says: "It has been been established in hosts of instances[24] that change of luminosity is, within limits, invariably attended by a corresponding change in the extension of the retinal zone within which the color of the stimulus is recognized. Its significance for the problem is self-evident. No determination of the relative extension of the various color zones can ever yield really comparative results unless it be accomplished by means of stimuli of equal brighness, or, speaking more correctly, of equal white-value" (p. 37). While we grant the significance of changes of luminosity or intensity in the sense in which Abney and Landolt use the terms, we do not admit that this aspect of the stimulus can be standarized in terms of white-value; nor do we grant that any definite evidence whatsoever can be gathered from the results we have quoted above, to show that changes in the white-value of a stimulus affect the limits of the retina's sensitivity to its color, provided the amount of colored light coming to the eye remains unaltered.

To sum up: (*a*) The white-value of a stimulus may be varied without altering the amount of colored light coming to the eye. This factor, then, may be isolated and its effect on the limits of sensitivity determined apart from any change in the physical intensity of the stimulus. (*b*) Unless this separation is made, we have no right to conclude that the white-value of the stimulus affects the limits of sensitivity. Baird, for example, drew this conclusion from work in which the separation was not made. (*c*) The confusion that exists with regard to color terminology

[24] Beside the three instances mentioned here, Baird cites in support of his position the work of Raehlmann, Chodin, Klug, Bull, Hess, and Hegg. How far their work can justly be cited in support of his position will be shown on pp. 51-53.

has been, we believe, in no small measure responsible for Baird's conclusion.

The terminology which we propose to use in this report may be outlined as follows: *Intensity of stimulus* will be used to indicate the energy of light-waves coming to the eye. *Intensity of sensation,* or *apparent intensity,* will be used as its correlative subjective term. So used, it will signify merely energy or voluminousness of sensation and will have no reference whatever to the white-value of a color. *Saturation of the stimulus* will be used to indicate the proportion of colored to colorless light coming to the eye. *Saturation of color* or *saturation of the sensation* will be used as its correlative term and will refer to the proportion of chromatic to achromatic quality in the sensation. The achromatic sensations will be designated by the terms *white, black,* and *gray;* and the terms *brightness* and *white-value* will be used interchangeably to indicate the lightness or darkness of a color.

(*b*) *The effect of intensity of stimulus.*

A dependence of color sensation upon the intensity of the stimulus has been recognized since the observations of Purkinje. Purkinje noted also that a color stimulus gave a less intense sensation in the peripheral retina than in the central retina. Since that time, it has been claimed (*a*) that with stimuli of minimal intensity, no color sensation is aroused; (*b*) that the light-waves arousing the different monochromatic sensations must be of different intensities to give liminal color sensations; that is, the eye is not equally sensitive to waves of different lengths; (*c*) that, progressively, greater intensity of stimulus is required to give sensation as the stimulus is moved from the fovea to the periphery; (*d*) that the extent of the color fields is determined within certain limits by the intensity of the stimulus.

The influence of changes in the intensity of the stimulus upon the sensation of color has been investigated by three methods: (1) by determining the effect upon the limens of sensitivity; (2) by determining the effect upon the j.n.d. of sensitivity; (3) by determining the effect upon the limits of sensitivity.

The effect upon the limens of sensitivity. When working by this method, the investigator started with a stimulus that was

below the threshold of sensitivity, and increased its intensity until the sensation of color was just noticeable. This increase in intensity was accomplished in three ways: (*a*) by increasing the illumination of a pigment surface, and consequently the amount of colored light reflected to the eye; (*b*) by increasing the intensity of the light used to give a spectrum; (*c*) by increasing the proportion of color in a mixture of colored and gray pigment stimuli.

The first method of increasing the intensity of the stimulus was used in central vision by Purkinje[25] and Aubert.[26] Purkinje observed a representation of the spectrum in pigment colors while daylight advanced. He found that blue was the first color to be seen in its true color tone, green next, yellow next, and red last. He made no measurements, however, of the amount of light required to give a just noticeable sensation. Aubert illuminated a pigment surface 10 mm. square by daylight admitted into a dark-room through an adjustable opening in a window. He found that with an opening ¼, ½, or 1 cm. square, no sensation of color was obtained. His results are given in the following table.

Opening in window	*Stimulus*	*Sensation*
¼-½-1 cm^2	all	no color
1¼-1½	orange	red
2	O,Y,R, rose	O,Y,R, rose
3	blue	blue
3	light green	brown
3½	light green	light green
5	green	blue
8	green	green

Aubert found that the eye was most sensitive in order to orange, red and yellow, blue, and least sensitive to green.

The second method was used by Raehlmann and Butz. They both used the Bunsen spectroscopic apparatus, which provides for changes in the intensity of the stimulus by means of the Nichol's prism. Raehlmann[27] determined the limens of sensitivity to the

[25] Purkinje, J. op. cit., 1825, II, p. 109.

[26] Aubert, H. Untersuchungen über die Sinnesthätigkeit der Netzhaut. Pogg. Annal., 1862, CXV, pp. 87-116.

[27] Raehlmann, E. Ueber Schwellenwerte der verschiedenen Spectralfarben an verschiedenen Stellen der Netzhaut. A. f. O., 1874, XX,1 pp. 232-254.

different spectral colors at the center of the retina, and at 30° and 60° in the horizontal nasal meridian. He found that the center was most sensitive in order to green, yellow, blue, violet, and red; and the periphery to yellow, blue, green, violet, and red. Butz's[28] procedure was as follows: He first determined the liminal value for each of his colors at the center. Starting with this value as unit, he determined how much this value had to be altered to give liminal sensation at 30° and at 60° in the horizontal nasal meridian. He found (*a*) that the sensitivity to each color increases from 0° to 30° and decreases from 30° to 60°; (*b*) that the amount of increase in sensitivity from 0° to 30° and the amount of decrease from 30° to 60° is different for the different colors, that is, the ratio of liminal sensitivity to any two colors is not the same from center to periphery; and (*c*) that the amount of the increase is greatest, and of the decrease is less in order for violet, yellow, blue, green, and red.

The third method was used by Aubert and Chodin, both of whom employed the Masson disc to find the limen of color sensitivity. Aubert[29] found that at the fovea, the eye is more sensitive to orange and yellow than to red and blue.. Chodin[30] found the sensitivity in the central retina to be greatest in order for orange, yellow, green, and least for blue. In the periphery, he found that the retina is more sensitive to blue and yellow than to red and green.

(2) *The effect upon the j. n. d. of sensitivity.* The effect of intensity upon the j. n. d. of sensitivity has been investigated by Lamansky and Dobrowolsky. Lamansky[31] used polarized spectral light, and worked in central vision. He found (*a*) that the j. n. d. of intensity for the different colors increases or, in other words, the sensitivity decreases, as the intensity of the stimulus is

[28] Butz, R. Vorläufige Mittheilungen über Untersuchungen der physiologischen Functionen der Peripherie der Netzhaut. Archiv für Anatomie und Physiologie, 1881, pp. 437-445.

[29] Aubert, H., Physiologie der Netzhaut. p. 136.

[30] Chodin, A. Ueber die Empfindlichkeit für Farben in der Peripherie der Netzhaut. A. f. O., 1877, XXIII,2, pp. 177-208.

[31] Lamansky, S. Ueber die Gränzen der Empfindlichkeit des Auges für Spectralfarben. Pogg. Annal., 1871, CXLIII., pp. 633-643.

decreased, and (b) that the j. n. d. of intensity is smallest, or the sensitivity is greatest in order for yellow and green, blue, and red. Dobrowolsky[32] in 1876 worked with the colors of the spectrum in central vision and at various points in peripheral vision. Employing standard and comparison fields, he altered the intensity of the comparison by rotating a Nichol's prism before the light-source until its intensity was just noticeably different from that of the standard. Considering that sensitivity varies inversely as the magnitude of the j. n. d., he found (*a*) that the sensitivity to the different colors decreases with increase of excentricity; and (*b*) that the comparative sensitivity for the different colors is the same in the center and in the periphery, that is, the order of sensitivity from greatest to least is in each case, blue, green, red. Later in 1881[33] he worked at seventeen different points in the intensity scale. He found again that the j. n. d. for blue is smallest, for green next, and for red largest. In addition he found that the ratio of sensitivity between any two colors as measured by the j. n. d. is not the same for different points in the intensity scale.

In regard to the methods used in the investigations reported above, it may be noted that in no one of the cases have the intensities of the stimuli used been measured and standardized. Tests of the comparative sensitivity of different parts of the retina to the same color and to different colors may be made with propriety by such methods, but not of a given part of the retina to the different colors. Conclusions can not, then, be drawn by the preceding investigators with regard to the comparative sensitivity either of the center or of the periphery of the retina to the different colors. They can, however, show that the center has not the same comparative sensitivity to the different colors that the periphery has. This conclusion may in fact be drawn from the results of all except Dobrowolsky. Dobrowolsky's results alone show that the center and periphery have the same relative sensitivity for all of

[32] Dorowolsky, W. Ueber die Empfindlichkeit des Auges gegen die Lichtintensität der Farben im Centrum und auf der Peripherie der Netzhaut. Pflüger's Archiv., 1876, XII, pp. 441-471.

[33] Dobrowolsky, W. Ueber die Veränderung der Empfindlichkeit des Augen gegen Spectralfarben bei wechselnder Lichtstärke derselben. Pflüger's Archiv., 1881, pp. 189-202.

the colors with which he has worked. A fair test of the comparative sensitivity of the eye to the different colors demands either that stimuli of equal energy be used or that the sensitivity be estimated in terms of units that can be compared. So far as the writer knows, no test of the sensitivity of the retina to color has ever been made with stimuli representing equal amounts of energy. Langley (1889) worked with stimuli of equal energy, but his test was for visual acuity.[34] Until stimuli of equal energy are used, it will remain an open question whether or not the retina, either in the center or in the periphery, possesses a different degree of sensitivity to each of the colors.

(*3*) *The effect upon the limits of sensitivity.* That change in the intensity of the stimulus has an effect upon the limits of sensitivity, has been shown by Abney[35] and others. Abney carried on an elaborate series of experiments with spectral light to show the effect of changes of intensity upon the extent of the color fields. He decreased the intensity of the stimulus by placing before it a gelatine wedge in the form of an annulus or ring. This annular wedge was one inch broad. It was graduated in thickness and its transparency was further regulated by black opaque particles which had been mixed with the gelatine in its semi-fluid state. The value of light admitted at O or at the thinnest part of the ring, was 10,000 units;[36] that admitted at 360° was 8 units. By interposing the annular wedge in a plane perpendicular to the path of the light and producing the proper amount of rotation, the intensity of the stimulus was reduced by graded amounts. Abney concluded that there is a simple relation between the intensity of the stimulus and the size of the color field.

The extreme position with regard to the effect of intensity upon the extent of the color field is taken by Landolt in the following passage. "In ein absolut dunkles Zimmer fiel nur durch eine kleine Öffung im Fensterladen directes Sonnenlicht. Dieses wurde auf das äusserste Ende des Perimeterbogens gelenkt. Während wir unser Auge ins Centrum des Bogens setzen, bracht man in die

[34] For discussion of Langley's work, see this paper p. 71.

[35] Abney, W. op. cit., pp. 155-195.

[36] No statement of the value of these units is made by Abney.

kleine, intensive beleuchtete Stelle farbige Papiere von möglichster Intensität der Färbung. Nun bewegtet sich das Auge langsam vom entgegengesetzen Ende des Bogens nach Scheitelpunkte zu und es zeigte sich dabei, dass wenigstens mit der innern Netzhautpartie alle Farben schon bei 90° erkannt wurden. Die Grösse des Objectes betrug weniger als 1 cm^2.

"Als dieselben Prüfungen auch mit Spectralfarben zu machen, entwarfen wir ein Sonnenspectrum im sonst dunkeln Zimmer und liessen es durch eine achromatische Linse auf einen Ende des Perimeters befindlichen Schirm fallen. Dieser hatte eine verändliche Spalte, mittelst welcher man die einzelnen Farben aus dem Spectrum isolieren konnte. Während wir nun wiederum nach langer Adaptation, und bei verbundenem zweiten Auge das eine Ende des Bogens fixierten, würde von einem Assistenten irgendeine Farbe des Spectrums auf die Spalte gelenkt, und wir drehten nun, unter stehter Fixation unserer Fingerspitze, welche sich auf dem Bogen bewegte, das Auge allmählig der Farbe entgegen. Es zeigte sich auch hier wiederum dass alle Farbe schon bei 90° erkannt werden, wenn sie intensiv genug sind."[37]

The first to recognize the need for making any sort of intensity equation of the stimuli used to investigate the relative sensitivity of the retina to the different colors was Ole Bull.[38] His purpose was to find an accurate method for investigating and measuring the sensitivity of the retina to the different colors. The first essential condition of the method, he considered, must be to equate the colors in saturation and brightness. Briefly, his method of equating in saturation consisted of using complementary colors of such relative intensity that they cancelled each other in a 1:1

[37] Landolt und Snellen. Ophthalmometrologie. Handbuch der ges. Augenheilk. von Graefe und Saemische, 1874, III., p. 70. The above quotation is given in full in the original in order to confirm (a) the statement made p. 16 concerning the interpretation of Aubert's statement of Landolt's results, and (b) the writer's interpretation, as opposed to Baird's, of Landolt's results, stated p. 18.

A brief summary of the above work is given by Landolt in Klinische Monatsblätter für Augenheilkunde, 1873, XI., pp. 376-377; and in Annales d'Oculistique, 1874, LXXI., pp.44-46.

[38] Bull, O. Studien über Lichtsinn und Farbensinn. A. f. O. 1881, XXVII, pp. 54-154.

ratio; that is, he used colors whose color-cancelling or color-quenching power was equal. It will be shown later in the paper (pp. 63-69), that this method is an anomoly, and, so far as the writer knows, is not justified in any investigation of color sensitivity that has yet been proposed. It certainly does not warrant conclusions concerning the relative limits of color nor the relative sensitivity of the retina to the different colors. Using this method of equating Bull concludes, however, that the retina, central and peripheral, is most sensitive to blue, then to yellow, then to red and green.

The second to recognize this essential condition was Hess[39] who made an exhaustive "Prüfung des Farbensinnes auf der peripherischen Netzhaut." Hess's object was primarily to furnish Hering with experimental evidence that would enable him to refute the Young-Helmholtz theory as modified by Fick to explain color-blindness. Young's view that congenital color-blindness is due to the absence of one of the three kinds of nerve fibres conceived by him to exist in the retina was adopted by Maxwell and Helmholtz, and extended by the latter[40] to explain the so-called peripheral color-blindness of the normal eye. Helmholtz believed that the peripheral retina is red-blind, and that this fact could be explained by assuming the absence of the red-sensing fibre. In 1873 Fick[41] and Leber[42] independently pointed out that this explanation of the peripheral color-blindness is inconsistent with the fundamental assumptions of the Young-Helmholtz theory. Fick declared that according to this theory the sensation of white can be aroused only by the stimulation of all three fibres in equal amounts, or to express it in another way, in balanced proportions. Now, if one fibre were inactive in the

[39] Hess, C. Ueber den Farbensinn bei indirectem Sehen. A. f. O., 1889, XXXV, pp. 1-62.

[40] Helmholtz, H. Handbuch der physiologischen Optik. 1st ed.,1867, pp. 301, 845.

[41] Fick, A. Zur Theorie der Farbenblindheit. Arbeiten aus dem physiol. Laborat. der Würzburger Hochschule, pp. 213-217.

[42] Leber, T. Ueber die Theorie des Farbenblindheit und über die Art und Weise, wie gewisse, der Untersuchung von Farbenblinden entnommene Einwände gegen die Young-Helmholtz'sche Theorie such mit derselben vereinigen lassen. Klin. Monatsblätter f. Augenheilk., 1873, XI, pp. 467-473.

peripheral retina, the sensation of white could never be produced in that part of the retina; but instead, the sensation proper to the combined action of the other two fibres would be aroused by white light. If, for example, in the middle region of the retina, the red-sensing fibre, and in the more peripheral regions both the red- and the green-sensing fibres were lacking, the sensation produced by white light in the former case would be blue-green, in the latter blue.[43] Further, if one or more fibres were absent in the outer zones of the retina, all the color sensations in these regions would be more saturated than those in the more central regions. For when all three fibres are present, as in the central retina, red, green, or violet light, for example, will stimulate not only its own proper fibre strongly, but will also stimulate the other two weakly. A certain amount of this total stimulation will be in the proportion to give the sensation of white, or more properly speaking, the sensation of gray, and the effect of this colorless component will be to reduce the saturation of the color sensation aroused. If, then, in the peripheral retina only one or two fibres are present, the colorless component will not be present to reduce the saturation of the color sensation, hence, other things being equal, the sensation of color should be more saturated here than that given in the central retina. Fick proposed the following modification of the theory to account for the color phenomena of the peripheral retina. He assumed that from the middle toward the periphery of the retina the relative excitability of the three nerve fibres to lights of the various wave-lengths constantly alters in such a way that at a certain distance from the fovea, namely, in the zone called by Helmholtz red-blind, the red-sensing fibres possess the same excitability as the green-sensing fibres toward lights of all wave-lengths;

[43] While in the opinion of the writer, Fick is correct in saying that white could not be produced in the extreme periphery by the action of two of the retinal fibres he is not right in saying what would be produced. For by a literal interpretation of the curves of excitation drawn by Helmholtz to represent his theory, none of the color experiences can be produced by the action of two fibres, excepting those in a small region of the spectrum in the violet. All other color experiences are produced by the combined excitation of all three fibres in some proportion.

and that further toward the extreme periphery, all difference between the relative excitability of the three fibres diminishes and finally disappears. In the red-blind zone, then, the intensity-curves for the red- and green-sensing fibres coincide, and in the totally color-blind zone, the curves for all three coincide. Curves drawn in accord with these assumptions will, it is contended by Fick, explain the types of color-blindness found in the peripheral retina without violating any of the fundamental principles of the Young-Helmholtz theory. Helmholtz accepts the essential points of this modification and incorporates them in his theory in his later edition of the Physiologische Optik.[44]

In order to disprove Fick's assumption that the relative intensity of response of the three fibres varies from center to periphery of the retina, and thus discredit the Helmholtz theory, Hess advanced three lines of argument. These arguments are as follows. In the first place he claims that there are three colors of the spectrum, a yellow, a green, and a blue, and a mixed color, a bluish-red, which are all invariable in tone from the center to the periphery of the retina.[45] In the second place, he shows that the proportions in which the complementary colors combine to produce white do not change for the different parts of the extramacular retina. And in the third place he attempts to show that a constant ratio of sensitivity to the members of each pair of complementary colors obtains throughout the retina. In order to make his third point he attempted to obtain red and green stimuli such that the red *Valenz* of the one, or, as he defines *Valenz,* its capacity to arouse red sensation,[46] should equal the

[44] Helmholtz, H. Handbuch der Physiologischen Optik. 2nd ed., 1896, p. 373.

[45] For a refutation of this point see footnote, p. 85.

[46] Hess defines the *Valenz* of his stimuli as their power to arouse color sensation. The writer would question this use of the term. According to its accepted chemical usage, the term might be applied with some degree of propriety to the power which, in terms of the Hering theory, a color possesses to combine with or cancel its complementary color, but scarcely to its power to arouse sensation. Hess, we presume, applies this term to the power of a color to arouse sensation because he assumes that this power is the same or at least equivalent to its power to cancel the complementary color. But since, as we shall show later (see p. 65), this assumption is far from correct, we strongly question the propriety of calling the power of a color to arouse sensation its *Valenz.*

green *Valenz* of the other. He describes his method of doing this as follows: "Als das Nächstliegende erscheint es nun, einen roth- und einen grün-wirkenden Pigmente den gleichen Roth- und Grünwerth dann zuzuschreiben wenn dieselben zu gleiche Theilen, z.B. auf dem Kreisel gemischt eine farblose Mischung geben" (p. 39). The same procedure was used in obtaining his blue and yellow stimuli. Using as stimuli, then, a red equal in cancelling power to a green, and a blue to a yellow, he determines the limits of sensitivity to these four colors. He finds that the limits for his red stimulus coincide with the limits for his green, and the limits for his blue with the limits for his yellow. The limits for blue and yellow, however, fall further out from the fovea than they do for red and green. From these results he concludes (*a*) the sensitivity of the retina from center to periphery falls off with the same rapidity for red as for green, and for blue as for yellow: and (*b*) the sensitivity for both red and green falls off more rapidly than for blue and yellow. Among his conclusions one also finds: "Bei den von uns mitgetheilten Untersuchungen ist die Prüfung des Farbensinnes auf der peripheren Netzhaut zum ersten Male mit genauer Berücksichtigung aller jener Bedingungen vorgenommen worden, welche unverlässlich sind wenn die mit verschiedenen Farben gewonnenen Resultate untereinander vergleichen werden sollen" (p. 56). These conclusions are open to the following criticisms: (1) His results do not warrant the statement that the sensitivity for red falls off as rapidly as for green, and for blue as for yellow. For this statement is based on the assumption that if in passing from center to periphery, sensitivity ends at the same point on the retina for two stimuli which have equal power to arouse sensation at the center, they must still have equal power to arouse sensation at the periphery, that is, sensitivity has fallen off as rapidly for one as it has for the other. Now in the first place this assumption begins with a fallacy. For his stimuli were not equated in power to arouse sensation but in cancelling power, and, as we shall show later, the power of a color to arouse sensation and its power to cancel its complementary color are not at all equivalent. And in the second place the assumption is itself incorrect,

for, because of the abrupt decrease in sensitivity as the limits are approached, the relative sensitivity to the two colors may have changed greatly and still their limits have coincided. We have found for example that working with colors of normal saturation under good illumination, it takes, varying with the color, a difference of 90° to 120° of color to make a difference of 1° in the limits. Hess should have determined the limens of color at various points from the center to the periphery of the retina, and have found out whether the ratios of the liminal values of his pairs of stimuli were equal at all of these points.[47] If so, the sensitivity to each member of the pair must have fallen off with equal rapidity from point to point, otherwise a change of ratio would have occurred. This method would have had the following advantages. (*a*) Account would have been taken of sensitivity at a large number of points from fovea to limits. (*b*) Much smaller changes in sensitivity would affect the limens than would affect the limits, especially until very near the limits. (*c*) No equation of stimuli with its attendant disadvantages would have been needed as long as the liminal values for each color were obtained in terms of the same stimulus all the way out. (2) But even if an equation made in terms of cancelling power were the equivalent of an equation made in terms of the power to arouse sensation, he would not have been justified in concluding, so far as his method of working is concerned, that the red-green sense decreases more rapidly than the blue-yellow sense, because this method afforded him no means of equating the intensities of the members of one of the pairs with those of the other pair. (3) Nor is he justified in his claim that he is the first to investigate the color sensitivity of the peripheral retina who has paid due regard to all the conditions which are essential if the results obtained for this sensitivity are to be compared with one another. One scarcely knows where to begin to refute a

[43] While in the opinion of the writer, Fick is correct in saying that white just noticeable difference of sensation could have been determined at each of these points in the retina for various points in the intensity scale. An account could thus have been had of the retina's sensitivity to the members of the pairs of colors at as many degrees of intensity of sensation as was desired.

statement so broadly overdrawn as this. The inadequacy of his treatment of the factors: general illumination, brightness of the stimulus, brightness of the surrounding field and preëxposure, is obvious to anyone who knows the effect of these factors. This inadequacy, however, will be noted at various other points in the paper. It will be sufficient at this point to consider only his handling of the factor, intensity, and that only briefly, for it will also be discussed in some detail at another point in the paper. Hess's problem was narrow and happens to furnish one of the very rare cases in which a subjective equation of the intensity of the stimuli used is justified. But his conclusion with regard to his method of handling the intensity factor is broad and specifically refers to all investigations of sensitivity in which results are to be compared. Such a conclusion is most assuredly not justified. In fact one might almost say that the converse of his conclusion is true. In no investigation of the comparative sensitivity of the retina to the different colors where absolute values are wanted is a subjective equation permissible. Such an equation begs the question at the outset. In such an investigation when an equation is needed, it should be made in terms of a common objective unit, for example, the unit of energy, and when an equation is not needed, the sensitivity should be estimated and expressed in terms of this common objective unit, or some other unit in terms of which results can be compared. In no case, so far as the writer is at present able to outline the field, is a subjective equation justified in an investigation of sensitivity except in certain problems relating to existing color theories or assumptions made for systematic purposes. And not even in these problems, so far as the writer is familiar with them, is an equation made in terms of cancelling power justified in an investigation of sensitivity.

Hegg[48] was the third investigator to attempt intensity equation. He posits three conditions to be fulfilled "für die Untersuchung des peripheren Farbensinnes." (*a*) The colors must be physiologically pure, that is, each color must be sensed similarly in all parts of the retina sensitive to it. (*b*) The colors must be

[48]Hegg, E. Zur Farbenperimetrie. A.f.O., 1892. XXXVIII., pp. 145-168.

of equal value in regard to brightness. (*c*) They must be equal in regard to color content (farbigen Gehalt). Concerning the third condition, Hegg writes: "Wenn es sich nun, was von theoretischen und praktischen Gesichtspunkten aus betrachtet von gleich grosser Wichtigkeit ist, darum handelt, die verschiedenen Farbempfindungen mit einander zu vergleichen, die physiologische Erregbarkeit entsprechender Nervenelemente nach einem gemeinsamen Massstab zu messen, so ist es selbstverständlich unumgänglich nothwendig, mit gleichgemessenen Reizen die Versuche anzustellen und unsere definirbaren, invariablen Farben anzupassen" (pp. 148-149). Hegg's "gleichgemessene Reizen" were obtained according to the method first used by Bull and endorsed by Hess. But this method of equating can not warrant any conclusion concerning the relative limits of peripheral sensitivity to the different colors. Hegg is then not justified in concluding "dass die Grenzen für Roth und Grün zusammenfallen. Die Grenze für Gelb sind durchwegs ca. 1° enger als für Blau, vielleicht wegen der stärkerem Brechung der blauen Strahlen?" (p. 166).

Baird[49] was the next to use this method of equating. He determined the relative extension of the different color zones, employing as stimuli light transmitted through gelatine filters. Like his predecessors he also concludes beyond what is justified by his method of working. He expresses his results as follows: "The zone of stable red is coextensive with that of stable green; the zone of stable yellow is coextensive with that of stable blue; and the yellow-blue zone is much more widely extended in all directions than is the red-green zone" (p. 61).[50]

[49] Baird. loc. cit.

[50] Fernald (Psychol. Rev. Monog., 1909, X, pp. 60-67) as a minor point in her study of the color sensitivity of the peripheral retina, made a hurried investigation in the nasal and temporal meridians of the limits of an Urroth and an Urgrün, an Urgelb and an Urblau that she claimed were of equal saturation. Her method of equating these stimuli was the same as that of Bull, Hess, Hegg, and Baird. The limits of these stimuli were, she states, determined hurriedly, most of the observations being made at intervals of 5° on the peripheral retina; for example, she states that Urgelb and Urblau were both seen at 85°, and not seen at 90°. In spite of the looseness of these determinations, she concludes that "the limits for the Urgrün are practically coextensive with those for the Urroth, and the fields for the

Bull, Hess, Hegg, and Baird all claim, then, that when the investigation is made with stimuli equated in brightness and in terms of cancelling power, the limits for *Urroth* and *Urgrün*, for *Urgelb* and *Urblau* coincide. It may be inferred from their work that they believe that at least one of the reasons for the non-coincidence of limits obtained by previous investigators is that the colors used were not equated in intensity. Evidence, however, can be derived from the work of Kirschmann,[51] 1893, that this can not at least be considered the sole reason. In Kirschmann's case, in fact, it apparently can not be considered as having any influence at all in producing the non-coincidence obtained. Although his pairs of colors were not equated in intensity, it is obvious that the deviations he obtained from coincidence of limits can not be explained as due to differences in intensity between his stimuli. Kirschmann mapped many meridians of the retina for the limits of sensitivity with both spectral and pigment stimuli. The pairs of colors were not equated in intensity. His color maps show that the outline of the field for each color is irregular in the different meridians, and is different from that of any other color. In general the field for blue is wider than that for yellow, but in certain meridians this order is reversed. The red field is generally wider than the green, but in some meridians the green is the same or wider than the red. Further, the difference between the limits of the colors in some meridians is considerably greater than in others. It is evident

Urgelb with those for the Urblau" (p. 65). In addition to applying to this work the criticisms passed above concerning the more careful work of Bull, Hegg, and Baird, all of whom drew conclusions similar to Fernald's, one may express surprise that work so sketchy should be considered as warranting any conclusion whatever. Fernald states, however, that differences of 5° in limits are too small to be of any significance (p. 66). She makes this statement apparently because with the varying conditions of illumination under which she worked, 5° seem to be a normal variation in limits. (It may be too that she considers that this gives her warrant for working only at intervals of 5°.) But as will be shown in the experimental section of this paper, a difference of 5° in limits represents a difference in sensitivity sufficient to raise the limen of sensitivity 200°. In more careful work, then, limits which varied 5° would hardly be considered as "practically coextensive."

[51] Kirschmann, A. Die Farbenempfindung bei indirectem Sehen. Philos. Studien, 1893, VIII., pp. 562-614.

that irregularities of this kind can not be due to a difference in the intensity of the stimuli employed, for if blue and yellow, for example, have the same limit when equated in intensity, their limits should retain the same general outline when the colors are of unequal intensity, and should differ only in their distance from the fovea. The zone for the more intense color should in every meridian be regularly some degrees wider than that for the less intense. Relative to the issue between Kirschmann and Bull, Hess, Hegg, and Baird, it is interesting to find that Bull, Hess, and Baird, who all claimed to find coincident limits in all parts of the retina for the paired colors obtained results which, when examined in detail, show the same deviations from coincidence as those which Kirschmann found. Baird, for example, determined the limits of the four principal colors in eight meridians, and concludes: "The results show that the zone of stable-red is coextensive with that of stable-green; that the zone of stable-yellow is coextensive with that of stable-blue."[52] An inspection of his table of results shows however, that this coincidence is extremely rough. In the results for every observer it is found that in some meridians the green field is wider than the red by 1°, 2°, or 3°; in other meridians, there is coincidence of limits; and in still other meridians, the green field is narrower than the red by 1°, 2°, or 3°. The same thing is true of blue and yellow. In general, but not in every meridian, yellow seems to be wider than blue on the nasal retina, blue wider than yellow on the temporal. Hess's and Bull's results show similar variations which are in some cases of even greater extent. It is evident, however, from their conclusion concerning the coincidence of limits that they regard these variations as insignificant, probably no more than their normal M.V. for the rough conditions under which they worked. But it should be borne in mind that 2° or 3° of difference in limits is not insignificant when conclusions are to be drawn from the results with regard to the relative sensitivity of the peripheral retina to the members of the pairs of complementary colors. Because of the abrupt falling off in sensitivity just before the limit is reached (see p. 117 ff.), a difference of

[52] Baird, J. op. cit., p. 61.

2° or 3° in the limits represents quite a large difference in sensitivity. For example, according to our results a difference of 2° in limits represents a difference in sensitivity sufficient to raise the limen for yellow 120°, for green 100°, for red 160°, for blue 170°; and a difference of 3° represents sufficient to raise the limen for yellow 210°, for green 215°, for red 210°, for blue 215°. Obviously the point is too important to be passed over without re-examination by better methods of working. The limits should be re-determined under conditions that do not give so large an M.V. This has been done by the writer with such a control of all the factors that cause variable results that her M.V. from observation to observation is less than 1°. The results obtained show that this difference in limits is real, and not an error due to any inaccuracy in the method of working. In some meridians the limits coincide, in others they diverge. In short, when the zones are outlined by lines connecting the points representing the limits in the different meridians, these lines for the pairs of colors do not coincide, but criss-cross in a very irregular manner. Therefore, on the basis of our own results as well as those of Kirschmann, the inference can not be drawn from the work of the men who have equated their stimuli in terms of cancelling power that coincidence of limits had not been obtained up to that time because stimuli so equated had not been used. Nor can the conclusion be drawn that even if the stimuli had been properly equated, coincidence of limits would have been obtained. In fact the converse of this conclusion can apparently be drawn.[53]

[53] The writer used as stimuli in these experiments the standard yellow, red, green, and blue of the Hering series. She did not use colors stable in tone as Bull, Hess, Hegg, and Baird claimed to use, because an exhaustive study of this question showed her that stability of tone for all meridians of the retina can be obtained for blue alone of the four principal colors. For a further statement in support of this point, see footnote p. 85. In any event, she is unable to see how the fact that the red and green of this series appear yellow in a small region of the peripheral retina could have any effect on the coincidence of limits for red and green, unless the limit for red, for example, is taken as the point at which all sensation of color disappears, regardless of whether this color is red or yellow. (The writer considered in her own experiments that the limit for a color was the point at which the color sensation lost all trace of its original quality.) However, even if the point at which all sensation of color whatever disappeared be

Therefore, the argument based upon it against Fick's modification of the Helmholtz theory to explain the color-blindness of the peripheral retina can also be refuted insofar as the results on the coincidence of limits can be considered as furnishing argument. This argument is, it will be remembered, that the sensitivity of the retina from fovea to periphery falls off as rapidly to one of the members of the pairs of complementary colors as to the other. It should be borne in mind, however, that the results needed in order to make this argument can not be obtained by a determination of the comparative limits of sensitivity alone.

considered the limit, the following consideration shows that the small component of yellow present in the peripheral retina in the sensations aroused by the red and the green of this series could not have caused the criss-crossing of limits any more than a difference in intensity could have caused it. In fact the point in reality reduces to a question of intensity. If, for example, one of the colors were stronger than the other, this color would have relatively more power to arouse this yellow component, than it would if the colors were of equal intensity. That is, the zone through which the yellow component would be sensed would be broader for this color than it would have been had both colors been of the intensity of the weaker color. And relative to the zone in which a yellow component was sensed, it would not be irregularly broader in some meridians for the stronger color and in other meridians for the weaker color, for in regions in which the yellow sense is relatively weak the zone would narrow for both stimuli. In short, while the influence of the yellow component might cause the zone of sensitivity to broaden for one member of the pairs of stimuli as compared with the other member, it could not cause it to become alternately broader and narrower, in other words, to criss-cross. It is just as obvious that difference in brightness can not be offered as an explanation of this criss-crossing, even if difference in brightness could be shown to have an effect on the limits of sensitivity to the pairs of colors in question. But, as we will show in the experimental section, difference in brightness can be considered as having no effect whatever on the limits of sensitivity. Hence on both counts, difference in brightness can be ruled out of consideration. It would seem, then, that we can conclude that the criss-crossing of limits represents a real relation of sensitivity to the members of the pairs of colors in the far periphery of the retina, even before the investigation is made with stimuli properly equated in intensity. Moreover, when we take into account the fact that a difference of 2° to 3° in the limits represents a large difference in sensitivity we have considerable reason for believing that the ratio of the sensitivity to one member of a pair of complementary colors to the sensitivity to the other member is not the same in all parts of the retina. The point will be definitely determined in the near future by the writer by a careful determination of limens from point to point in many meridians of the retina, with stimuli which consist of lights of spectral purity, measured in terms of a common unit of intensity.

Knowledge is needed of the comparative sensitivity all the way out. Moreover, this knowledge must be based on actual determinations at points not widely separated from each other. The limit is only one of the points at which determinations should be made. In fact, it can scarcely be said to sustain any more important relation to the problem than any other point far removed from the fovea. Furthermore, conclusions can not be drawn from work done by the method of limits with regard to the comparative falling off in sensitivity from fovea to periphery unless it has previously been inferred from a comparison of the results at the center with the results at the limits what the comparative sensitivity should be at the points intervening, as was done by Hess. But this is wholly unjustifiable, for if there is one principle above another that the determinations of sensitivity in the peripheral retina bring out, it is that inferences can not be drawn about sensitivity between points at all widely separated. In fact, practically no conclusions of systematic importance can be justified at all from results obtained by the method of limits, although conclusions of great importance to theory have frequently been drawn from such results. The method of limens should be used instead, for by means of it accurate account can be taken of sensitivity at any point that is desired.[54]

A brief survey of our discussion of intensity shows the following facts:

1. The intensity of the stimulus is a factor influencing both the limens and the limits of color sensitivity. It should, therefore, be carefully standardized in all determinations of sensitivity.

2. The conclusions that have been drawn up to this time concerning the comparative sensitivity of the retina to the different colors have not been justified because of the methods of working that were used in the investigations from the results of which they were drawn; for (*a*) either no standardization of the intensity of the stimuli used had been made; or (*b*) this standardization had been made by an improper method. From the results of

[54] As stated in footnote p. 83, if a more exhaustive study of the point is wanted, the results of the method of limens should be supplemented by a determination of the just noticeable difference in sensation for various points in the intensity scale at each point of the retina investigated.

the work as it was done the following conclusions alone can be drawn: (*a*) The comparative sensitivity to the different colors is not the same at the center as it is in the periphery of the retina. This conclusion may be drawn from the results of Chodin and Raehlmann and Butz for the limens of sensitivity. And (*b*) it is not the same for the members of the pairs of complementary colors at all points even in the small region of the peripheral retina that has been examined, namely in the region comprehended by the criss-crossing limits for these colors. This conclusion may be drawn from Kirschmann's results, from our own, also from those of Bull, Hess, and Baird as shown in their tables giving the limits of their stimuli in different meridians.

3. Broader conclusions than this are justified only when the comparative sensitivity of the retina to the different colors is determined with stimuli properly standardized in intensity. As has been briefly pointed out, the comparative limits of sensitivity can be determined only when the intensities of the stimuli used have been standardized in terms of a common objective unit, for example, the unit of energy; and the comparative limens only when the intensities of the stimuli used have been estimated in terms of this common objective unit, or some other unit in terms of which results can be compared.[55] This point will be discussed more fully later in the paper (see p. 63 ff).

(*c*) *The effect of brightness of the stimulus.*

There has been very little discussion by previous investigators whether the brightness or white-value of a color affects the retinal limits of sensitivity to that color, and whether this aspect of the stimulus need then be taken into account in determining the relative extent of the color zones. We have already shown that in such work as there has been, the brightness factor has been obscured by and confounded with the intensity factor.

The confusion of the intensity and brightness aspects of color was noted by Langley in an article entitled *Energy and Vision, Philos. Mag.*, 1889, XXVII, 5th ser., p. 1. Langley writes: "While it is quite a familiar fact that the luminosity of any spectral ray increases proportionately to the heat in

[55] It is scarcely needful to point out that the same kind of standardization is required in order to determine the comparative j. n. d's. for the different colors.

this ray, and indeed is but another manifestation of the same energy, I have recently had occasion to notice that there is, on the part of some physicists, a failure to recognize how totally different optical effects may be produced by one and the same amount of energy according to the wave-length in which this energy is exhibited. I should not perhaps have thought it advisable to make this last remark, were it not that there has appeared in a recent number of *Wiedemann's Annalen* a paper by H. F. Weber on "*The Emission of Light*", in which he tacitly makes the assumption that the luminosity of a color is proportionate to the energy which produces it, an assumption which it is surprising to find in a paper of such general merit and interest."

This confusion, insofar as it has not been due to a misinterpretation of terms, seems to have arisen because the usual method of varying the one factor has necessitated an accompanying variation of the other. Further, the fact that when the intensity or energy of spectral light is increased to a maximum, the color is lightened until white is produced,[56] has been responsible for the view that light colors are more intense than dark colors, and has led to the custom of determining the energy or intensity of colored light by photometric methods. The photometric method can not, however, be used directly for estimating the intensity of colored light for two reasons. (*a*) Direct radiometric measurements of energy show that the relative values of the colors of the spectrum as determined by the two methods do not at all coincide. The photometric curve, for example, of the spectra of all light sources of normal intensity is highest in the yellow-green and lowest in the blue and red. The radiometric curve of the visible spectrum of sunlight of the same intensity is, on the other hand, according to Langley,[57] highest in the red near the C line and lowest in the violet; while the radiometric curves of the visible spectra of most of the artificial sources of light, such as the Nernst, tungsten, and arc lights, are highest in the extreme red and lowest in the violet. (*b*) The relative photometric values of the colors of all spectra differ widely for different intensities of the same light-

[56] This statement is true only if the original color has maximal saturation. When one increases the intensity of colors whose original intensity is slight, red and yellow become lighter, blue and green darker. These brightness changes are known as the Purkinje phenomenon.

[57] Langley, Energy and Vision. Amer. Journ. of Science, 1888, XXXVI, 3rd Ser., pp. 359-379; also Philos. Mag., 1889, XXVII, 5th Ser., p. 1; and Invisible Solar and Lunar Spectra, Philos. Mag., 1888, XXVI., 5th Ser., pp. 505-520.

source. For medium intensities, for example, the curve is highest in the yellow-green and lowest in the blue. But as the intensity is decreased the curve levels, while its maximum height shifts to the green and its minimum to the red. In short, the photometric value of a color is not a constant but a variable function of its intensity. From the above consideration, it is obvious, then, (*a*) that the photometric method can not be used to estimate the relative intensities of the colors of the spectrum even for a single intensity of light-source unless for each point of the spectrum considered a factor be determined which will transform the photometric into the radiometric value; and (*b*) that it can not be used over a wide range of intensities of light-source unless this calibration be previously made for each degree of intensity used. Furthermore, the brightness factor is not inseparably bound up with the intensity factor. It can be isolated. When, for example, one uses a constant amount of colored light, spectral or pigment, and mixes with it a constant amount of white, black, or gray, one obtains stimuli which contain an equal amount of colored light but which have different brightnesses. Up to the present this method of isolating the brightness factor to test its influence has been employed only by Hess, and in his work, as we shall see, it has been used very inadequately.

The discussion whether the brightness of the stimulus affects color sensitivity was raised by Aubert. Aubert was unable to reach positive conclusions concerning its influence. He was led to a consideration of the question by the outcome of an investigation planned to determine the influence of visual angle upon the perception of color in central vision. His results showed that the liminal visual angle was different in case of the different colors, and further, that it differed when the colors were viewed upon white and black grounds. In the discussion of these results he writes: "Zum Theil beruhen diese Verschiedenheiten wohl auf einer verschieden starken Affection des Farbensinnes, zum grösseren Theil aber wohl auf Helligkeitsdifferenzen. Wir haben dabei drei Momente zu berücksichtigen, nämlich die Farbennüance, die Farbenintensität, und die Helligkeitsdifferenz oder den Contrast der Pigmente."[58] These *Momente* Aubert defines as

[58] Aubert, H. Physiologie der Netzhaut. Breslau, 1865, p. 111.

follows: *Farbennüance* is the sensation given when a color is mixed with white, black or gray. A light blue, for example, contains more white and less blue light than a saturated blue.[59] *Farbenintensität* is defined as "the impression which is dependent on the intensity of colors: in case of spectral colors, on the amplitude of vibration; in case of pigments, on the intensity of the illumination." "Maxwell," he says, "calls this *'shade'*: one color may be lighter or darker than another."[60] Whether or not Aubert also uses the term *intensity of color* as synonymous with *white-value* is open to question. There is evidence in his discussion, however, that he uses it synonymously with *brightness.* For example, when discussing *Farbenintensität*[61] he claims that the intensity factor cannot be made standard because it is impossible to determine which of two colors is the brighter, and because the photometric values of the spectral colors is unknown, the results of Melloni, Dove, and Helmholtz on this point differing widely. But whether or not *brightness* means for him also *white-value* depends upon what he thinks is measured by the photometric method. *Helligkeitsdifferenz* is the brightness relation between a color and its background.[62] The three factors, then, that Aubert believes we have to consider are (*a*) the amount of colorless light mixed with the color; (*b*) the intensity or brightness of the color; and (*c*) its contrast with the background. The first of these factors, he contends, influences color perception. He finds that the more colorless light is mixed with a pigment color, the the greater must be the illumination at which the color can be liminally sensed; in other words, when the pigment surface reflects a small amount of colored light, the intensity of its illumination must be proportionately greater to give liminal sensation.[63] The third of these factors he also considers very important. Colors have different limens and limits of visibility on white and on black grounds. Now the brightness of the

[59] Aubert, H. loc. cit.

[60] Aubert, H. op. cit., p. 108.

[61] Aubert, H. op. cit., p. 111.

[62] Aubert, H. op. cit., p. 112.

[63] Aubert, H., Untersuchungen über die Sinnesthätigkeit der Netzhaut. Pogg. Ann. d. Physik und Chemie, 1862, CXV, p. 111, 114.

color determines how great the difference is in the two cases. Blue, for example, is very dark. It is in great contrast to the white field and in much less contrast to the black. Its limit in each case is respectively 15° and 36°,—a difference of 21°. Red is less dark. Its limits with the white field is 16°, with the black 30°,—a difference of 14°. Green is a lighter color and more nearly of mean brightness between white and black. In this case the difference in its limits with white and black fields is only 4°. Aubert contends "dass die specifische Farbenwahrnehmung an der Seitentheilen der Netzhaut um so eher in eine blosse Wahrnehmung von Hell und Dunkel übergeht, je stärker dieselbe mit der Umgebung contrastiert."[64] This is stated again in the *Physiologie der Netzhaut:* "Contrast und Helligkeit der Farben sind von grossem Einfluss auf die qualitative Farbenempfindung, so wie auf die Grösse der Netzhautparthie, innerhalb welcher die Farben empfunden werden sein."[65] In this regard, then, the difference in the brightness of the colors has an effect on color sensitivity only when the brightness of the surrounding field is made the same for all of the colors. But since it need not and should not be made the same for all of the colors in any investigation of sensitivity, unless the purpose of the investigation is to test the effect of surrounding field on the different colors, this case may be ruled out of consideration. The second *Moment,* the intensity or brightness of the colors, Aubert finds himself unable to isolate. He works with pigment stimuli and can not alter the intensity without at the same time changing the proportion of colored to colorless light reflected from his stimuli; or as he calls it, the nuance of the color. That is, in order to change the intensity of the color, he is compelled to change the amount of white, black, or gray mixed with it.[66] Further, he thinks it is often impossible to determine which of two colors is the brighter.[67] However, his experiments to determine the relative intensity of illumination necessary for the

[64] Aubert, H. Ueber die Grenzen der Farbenwahrnehmung auf die seitlichen Theilen der Netzhaut. A. f. O., 1857, III_2. p. 54.

[65] Aubert, H. Physiologie der Netzhaut. Breslau, 1865, p. 122.

[66] Aubert, H. op. cit., p. 153.

[67] Aubert, H. op. cit., p. 111.

liminal visibility of the different colors lead him to think that the brightness of color is not in itself a factor. In these experiments he finds that when the colors are arranged in order according to the intensity of illumination necessary for their perception, they are from least to greatest: orange, yellow, red, light blue, light green, blue, green. But when the illumination is decreased so that all the stimuli are seen as grays, they differ in brightness from light to dark in the sequence: yellow, light blue and green, blue, green, orange, red. Since the order differs in the two cases, he concludes that the differences in the perceptibility of the colors can not be due to their difference in brightness. He says: "Vergleicht man diese Ordnung der Farben nach ihrer Helligkeit mit ihrer Reihenfolge hinsichtlich ihrer Erkennbarkeit bei beschränktem Lichtzutritt, so sieht man, dass die Helligkeit der Pigmente nicht die Ursache seyn kann, dass diese oder jenes Farbenquadrat bei einer geringeren Lichtintensität farbig erscheint."[68] His final conclusion from this discussion of the three *Momente* is that the colors are not equally perceptible; but it can not be determined in how far this depends upon color tone, color intensity, or color nuance.[69]

In clearing the ground by the discussion of these three *Momente,* Aubert, then, finds himself utterly unable to answer the question: Does the brightness difference between two colors affect the sensitivity of the retina to these colors? because he can not isolate the factors involved for investigation. He, however, recognizes the possibility that brightness difference may affect color sensitivity and for this reason is inclined to think that his own may be only a rough determination. He writes: "To obtain a fine estimation, the influence of brightnesses must be eliminated; and pigments of equal intensity and nuance must be observed upon a background of the same brightness as the pigment. But we do not possess such pigments; and since the photometric value of prismatic colors is not known, an exact estimation of the liminal visual angle at which the colors can be sensed seems impracticable."[70] As will be shown later, Bull

[68] Aubert, H. Pogg. Ann. d. Physik und Chemie, 1862, CXV, p. 105.

[69] Aubert, H. Physiologie der Netzhaut. Breslau, 1865, p. 123.

[70] Aubert, H. op. cit., p. 112.

and Hegg take this statement as authority to equate colors in brightness for investigations of the peripheral limit of color sensitivity. It is obvious, however, that the statement contains no real authority for the equation of colors to be used even in investigations of color sensitivity in central vision, because Aubert confesses that he is unable to demonstrate whether or not the brightness of a color affects the retina's sensitivity to that color. He has merely expressed a belief that in fine determinations the equation should be made. Baird, as we have seen, also claims Aubert as authority for equation in brightness, but apparently he has not even this much basis upon which to rest his claim, for in Baird's long list of references to Aubert, none is found to the section containing the statement quoted above. This statement occurs in Aubert's discussion of the influence of visual angle on the perception of colors in direct vision (Physiologie der Netzhaut, pp. 108-115). Baird's references to the *Physiologie der Netzhaut* are pp. 89-105; 116-124. As has been shown on p. 13, Baird apparently gets his authority from a discussion in which Aubert is clearly concerned not with the white-value of color but with the total effect of changes in the general illumination. Furthermore, so far as the writer has been able to ascertain, Aubert nowhere else gives as much authority for equating in brightness as is contained in the statement selected by Bull and Hegg upon which to base their claim.

Aubert's opinion that the effect of the brightness of a color upon the retina's sensitivity to that color can not be determined was also held by Chodin who was unable to isolate brightness and intensity from each other.

Chodin writes:[71] "Es bleibt nur übrig die Farben bei gleicher Sättigung und bei mittlerer Lichtintensität zu vergleichen, und da sie unter dieser Bedingung von verschiedener Intensität sind (vielleicht sind die idealen Farben von gleicher Helligkeit, wie Hering sich vorstellt aber wir wissen dies nicht und können es nicht wissen) so liegt es sehr nahe anzunehmen, dass diese verschiedene Helligkeit eine constante Eigenschaft der Farbe selbst sei, welche, wenigstens in merklichen Grade, weder vermehrt

[71] Chodin, A. op. cit., p. 178.

noch vermindert werden kann ohne eine Veränderung des Charakters der Farben selbst herbeizuführen." Chodin goes on to point out one of the difficulties of attempting to obtain stimuli of equal brightness. In case of some of the colors, both spectral and pigment, a change of quality or tone takes place, when, in their state of greatest saturation, their brightness is altered. For example, spectral yellow when darkened gives a reddish-yellow or brown appearance, and the yellow of pigment paper, a decided olive-green appearance. Blue, when altered in brightness, appears reddish. These color changes have been recorded by Chodin, Brücke,[72] Hegg,[73] Rood,[74] and others. They are marked and are particularly troublesome in that the blue and yellow stimuli, which undergo the greatest changes in quality, are the stimuli that must be altered the most in order to be equated in brightness.

Ole Bull[75] was the first to mention the problem under discussion in its specific relation to the determination of peripheral color limits. He made no direct test of the influence of the brightness of the stimulus upon sensitivity, but quoted as authority for equating his own stimuli Aubert's statement that for fine determinations of color sensitivity brightness differences must be eliminated. Like Aubert, he was unable to show that the brightness of the stimulus constitutes a factor, but unlike Aubert he does not recognize the need for demonstrating this point. He thus equated his stimuli apparently without ever even having realized the need to investigate whether or not this equation should be made.

Hess[76] seems to have been the only investigator who has made any attempt whatever to determine whether a light and a dark color of equal intensity have the same or different limits of visibility in the peripheral retina. His test was simple and was applied only to one color. Using two stimuli, the one composed

[72] Brücke. Wiener Berichte, 1865, LI, p. 10.

[73] Hegg, E. loc. cit.

[74] Rood. On the Effects Produced by Mixing White with Colored Light. Phil. Mag., 1880, X., p. 209.

[75] Bull, O. op. cit., p. 93.

[76] Hess., C. op. cit., p. 42.

of 180° *Urgün* and 180° white, the other of 180° *Urgrün* and 180° black, he compared their limits in the horizontal temporal meridian. In each case the stimulus was exposed on a background whose brightness was the same as that of the darker stimulus. Hess found the limit of the dark green to be 25°, of the light green 13°. The value of this brief test lies in that it shows a recognition of the need to investigate whether or not the brightness of the stimulus affects the limits of sensitivity, before an attempt is made to equate in brightness. Hess's method of determining the influence of the factor is, however, open to criticism in two regards. In the first place he made no determination of the amount of brightness difference existing between the colors used. He arbitrarily altered the brightness of green 180° in both directions, that is, toward both black and white. He gives no reason for this choice of 180° of variation of the brightness component. He does not tell us, for example, whether it represents as much brightness difference as there exists between his stimuli, or whether it represents more, or less. If it had represented less, the test would not have possessed due rigor. If, on the other hand, it had represented more, the test would not have been fair for two reasons. (*a*) Brightness mixed with color inhibits color sensation. This inhibitive action is greater the nearer the brightness mixed with the color approaches white, and is less the nearer the brightness approaches black.[77] It is obvious, then, that the difference between the amounts of the inhibition of the color by the white and that by the black would increase as the amount of the brightness component increases. If, then, in the above test, Hess had mixed with *Urgrün* in turn amounts of white and black that represented a brightness variation greater than the brightness difference that exists between the standard colors, he would have had a greater difference between the amounts of inhibition in the

[77] As will be shown in the experimental section of this paper, this may be stated as a general law of the action of brightness on all colors for all parts of the retina with the exception of a region within 5° of the limits of sensitivity to red and yellow, as determined with stimuli of normal saturation and intensity. Within this narrow zone the saturation of red and yellow is reduced more, apparently, by black than by white.

color mixed with white and the color mixed with black, and consequently a greater difference between the intensities of the sensations aroused by them, than he would have had, if a brightness change equal to that existing between the standard colors had been used. His results, then, can not be taken as evidence that the proper amount of brightness change necessary to render the standard colors equal in brightness would change the limits of color sensitivity. Much less can they be taken to show that the amount of brightness difference actually existing between the standard colors acting in conjunction with the greater amount of light coming from the standard colors than from his weakened stimuli would affect the limits of sensitivity.

(*b*) In Hess's experiment, the color stimulus containing 180° *Urgrün* and 180° white, and that containing 180° *Urgrün* and 180° black both possessed less physical intensity than would stimuli in which less brightness variation had been made. That the degree of intensity of the stimulus is a potent factor in the determination of whether or not the difference in brightness between a light and a dark color of equal physical intensity affects the peripheral limit of sensitivity to that color will be shown in the experimental part of this paper (pp. 104 ff). The results of this work, however, may be anticipated briefly at this point. As has been stated, the action of white when mixed with color inhibits the apparent saturation of the color more than black does. The question under consideration is whether the apparent saturation of a dark color is sufficiently greater than that of a light color of equal physical intensity to widen the peripheral limit of sensitivity to the dark color. Now a determination of the limen of sensitivity to color at a number of points from the fovea to the limits of sensitivity to color shows that the sensitivity to a color decreases slowly from the fovea to a point about 5° within the limit of sensitivity to that color as determined with a stimulus of full saturation,—the point varying slightly for the different colors in its distance from the color limit. From this point on toward the limit, the sensitivity falls off very rapidly. A large increase in the limen is present from degree to degree in this region, often as great as 90° per degree of retina traversed. It

is obvious, then, that if the intensity of the colored stimulus is sufficient to cause its limit to fall within this zone of rapid decrease in sensitivity, the difference in saturation between a light color and a dark color of equal physical intensity would not be sufficient to cause a widening of the limits. On the other hand, if a smaller intensity of color were used so that the limit of the color occurred within the retinal region where color sensitivity alters but slightly from point to point, the greater apparent saturation of the dark color would be sufficient to allow the color to be visible at a point where the light color of less apparent saturation though of equal physical intensity is not sensed. Now the limen for the different colors when mixed with white at the point where the rapid decrease in sensitivity to each begins, is as follows: 120° of yellow; 130° of green; 135° of red; and 145° of blue. These values, then, represent the amount of color that would have to be had in the stimulus to which white had been added to make the limits of sensitivity to them fall just at the boundary between the zones of gradual and abrupt decrease in sensitivity. And since black inhibits color less than white, even less color would be required in the stimuli to which black had been added to make the limits fall at this point. For any amount of color greater than these values, the limits would fall within the zone of rapid decrease. One could, then, add white to his stimuli by amounts varying from 0° to 215°-240° for the different colors, and black in still greater amounts, and still work within the zone of abrupt decrease. And as long as one works within the region of abrupt decrease, the limits for the colors lightened and darkened by the above amounts will coincide. It need hardly be said that 215°-240° multiplied by two to express the variation in both directions, represents a much greater brightness difference than exists between the standard colors. On the other hand, for any amount less than the above values, the limits would fall in the zone of gradual decrease. Now Hess's stimuli contained less than this amount of color because his *Urgrün* contained only 244° of green and 116° of blue. 180° of this *Urgrün* would, then, contain but 122° of green and 58° of blue. The intensity of this stimulus was, therefore, so small that ac-

cording to our results the limits for both component colors would fall in the zone of gradual decrease of sensitivity. In this zone the greater saturation of the color when mixed with black would cause it to be sensed farther out than the color when mixed with an equal amount of white; that is, the limits for the darkened color would fall further from the fovea than the limits for the light color, as Hess found them to do. In this regard, too, then, it may be said that if in Hess's test, a brightness change was made greater than the brightness difference between the standard colors, and consequently a stimulus was used having smaller intensity than it would have had, if the proper brightness change had been made, the test would have been unfair because the degree of intensity of the stimulus is a factor determining whether or not there is a different limit for light and dark colors of equal physical intensities.

While it is sufficient for our point to show in what respects Hess is open to criticism for arbitrarily selecting 180° of brightness variation without making any determination of how much need be made, a word may be added to show that 180° of brightness variation is much more than was needed. For, the table in which Hess[78] states the values of the stimuli determined by different observers to be equal in cancelling-action and brightness, shows that in no case was a variation of more than 133° made in one direction, that is, toward either white or black. It is often difficult to see just how much variation was made, because in the majority of cases both black and white were added, hence the net variation was less than the value of either. For example, 105° of yellow, 60° of white, and 195° of black were found by one observer to be equal in cancelling action and brightness to 85° of blue, 84° of white, and 191° of black; for another observer, 200° of red, 48° of blue, 66° of black, and 46° of white were equal in cancelling action and brightness to 188° of green, 39° of blue, and 133° of black. But in no case is the variation in one direction more than 133°, or less than 91°. We may conclude, then, that by his choice of 180° of brightness variation by means of which to compare the limits of a light and

[78] Hess, op. cit., pp. 45-46.

a dark color of equal physical intensity, he has, roughly speaking, made his brightness variation one and one-half times greater and his intensity only four-fifths of what it should have been, judging from the greatest variation he had to make for his brightness equation. Either one of these items: the overestimation of brightness change or the underestimation of intensity is sufficient both to render his test unfair and, moreover, to account for a very considerable difference in the limits for color mixed with white and for the same color mixed with black.

The second point of criticism of Hess's test is in regard to his method of controlling the brightness of the surrounding field and of the preëxposure. He did not use the proper conditions of brightness of screen and of preëxposure card. He used a screen and a preëxposure which were of the same brightness as the dark stimulus, both in the tests with the dark and with the light color. There was, then, a considerable amount of white added to the light stimulus by contrast from the dark background and by after-image from the dark preëxposure over and above the white that was added by objective mixing. Thus while he aimed to add equal amounts of white and black to his pairs of stimuli, he really added much more white than black. Now, we have found that white subjectively aroused apparently has as much effect on the color excitation as white objectively aroused. His test was thus again rendered unfair by his lack of proper conditions with regard to the brightness of the surrounding field and of the preëxposure. The surrounding field and the preexposure should have been made in each case equal in brightness to the stimulus.

Hess does not appear to have realized the importance either of the brightness of the surrounding field or of preëxposure as factors influencing color limits. He generally equalized the brightness relation between stimulus and background because he seemed to think that accuracy of judgment was fostered thereby,—that one can more readily tell when the color has disappeared from a given stimulus when there is no brightness difference between the stimulus and the background to confuse the judgment.[79] The preëxposure he made of the same quality

[79] See Hess, op.cit., p. 25.

and brightness as the background. No reason was given for this procedure.[80] Thus in the above test, he overlooked the diminution in the intensity of the sensation aroused by the lighter stimulus due to the contrast from the surrounding field and to the after-image from the preëxposure,—a diminution which is also in itself sufficient to account for quite a large difference in the limits for a light and for a dark stimulus of the slight degree of intensity used by Hess. Hess's results, then, assuredly can not be considered as showing that the brightness difference between the normal colors affects their limits of sensitivity.

Hegg,[81] like Bull, made no test to determine whether the brightness of the stimulus constituted a factor in the determination of color limits. He gives no reason for the attempt he makes to equate in brightness, other than the fact that Aubert and Bull had mentioned the necessity for this procedure.

Baird was the next to state that the stimuli used to investigate the peripheral color sense must be of equal brightness. His reasons for making this statement have already been discussed in part (pp. 12-19) in order to show how the prevailing confusion with regard to terms has led to misinterpretation. To connect this preceding discussion with what is to follow, a few words to résumé will probably be of service here. It will be remembered that like Bull and Hegg, Baird made no attempt to determine whether or not the brightness or white-value of a color exerts an influence on the limits of sensitivity to that color. Unlike Bull and Hegg, however, he claims to be able to derive authority for equating stimuli in white-value from the work of many investigators,—primarily from that of Aubert,[82] Landolt,[83] and Abney,[84] but also from Raehlmann,[85] Chodin,[86] Klug,[87] Bull,[88]

[80] See Hess, c. op. cit., p. 44.
[81] Hegg, E. op. cit., p. 146.
[82] Baird, J. op. cit., p. 12.
[83] ibid, p. 16.
[84] ibid, p. 31.
[85] ibid, p. 17.
[86] ibid, p. 20.
[87] ibid, p. 20.
[88] ibid, p. 22.

Hess,[89] and Hegg.[90] With regard to these sources of authority, it has been shown (*a*) that Abney and Landolt do not even claim that brightness difference affects the sensitivity of the retina to color, and that Aubert does not in the references given by Baird; (*b*) that Bull and Hegg equated their stimuli in brightness merely because Aubert had expressed the belief that such procedure is necessary in making fine determinations of color sensitivity, but since Aubert was unable to demonstrate this necessity, their reason for making the equation has no value;[91] and (*c*) that Hess's test, upon the results of which he bases his conclusion with regard to the need to equate, was both incomplete and wrongly devised. We have yet to show, then, that no authority can be derived by Baird from the work of Raehlmann, Klug, and Chodin. A claim to authority was derived from the work of Raehlmann and Klug by misinterpretations similar to those made in the cases of Landolt and Abney. Raehlmann and Klug both worked with spectral light and sought to find the effect of decreasing the intensity of the colored light upon the limits of sensitivity. Raehlmann[92] decreased the intensity of his stimuli as follows: Light reflected from a heliostat was passed through a prism and the spectrum from this source was thrown upon a screen, which may be called $screen_1$, the distance of which from the light-source was kept constant. This screen contained an opening for the transmission of the colored light. The amount of light transmitted could be regulated by the size of this opening, and the quality could be regulated by shifting the position of the opening along the spectrum. The colored light fell upon a second screen, $screen_2$, so arranged that its distance from $screen_1$ could be varied. In two ways, then, could diminution of

[89] Baird, J. op. cit., p. 27.

[90] ibid, p. 29.

[91] As has been shown, pp. 40-44, Baird, as well as Bull and Hegg, might have had some justification in citing Aubert's authority on the question of brightness equation, from the latter's statement that all brightness differences must be eliminated from stimuli used to make fine determinations of color sensitivity. But this statement of Aubert's is not included in the references to Aubert from which Baird drew his authority.

[92] Raehlmann, E. Ueber Verhältnisse der Farbenempfindung bei indirectem und directem Sehen. A. f O., 1874, XX_{II}, p. 18.

intensity be produced: (*a*) by decreasing the size of the opening in $screen_1$, and (*b*) by increasing the distance between $screen_1$ and $screen_2$. Both methods were used by Raehlmann for producing what he terms *die Abnahme der Lichtstärke*. A change in brightness may have been incidentally produced, but this aspect of the stimulus was of no concern to him. He found that a decrease in intensity decreased the zone in which a color was sensed in its characteristic tone; he most assuredly does not claim, however, as Baird says he does that "the color limits were found to vary with changing brightness of stimulus" (see Baird, p. 17) in the sense in which Baird uses brightness, namely, as white-value. Klug[93] used a method somewhat similar to Abney's. He weakened a beam of light by interposing respectively one, two, and three thicknesses of ground glass, and found that the color limits were narrowed in each successive case. Thus he also made no attempt to isolate the effect of the brightness of the stimulus, and his work can not be cited as having any bearing on that problem. In Chodin's work, as we have already seen, the advisability of equating in brightness was discussed and decided against because of lack of evidence for the need of equating and because of the changes in color tone produced by changing the brightness of the colors. In giving Chodin as one of his authorities for equating, Baird refers to the passage in Chodin's article quoted in the original in this paper, pp. 44-45.

Baird writes: "Chodin remarks in his introduction: 'It is self-evident that in comparing the retinal sensitivity to different colors, the color stimuli employed must be of equal brightness and of equal saturation.' But this very essential condition was not fulfilled in his own experiments" (see Baird, p. 20). Baird has here again made a misinterpretation. The rather free translation of Chodin's statement: "Es bleibt nur übrig die Farben bei gleicher Sättigung und bei mittlerer Lichtintensität zu vergleichen"[94] and the failure to read carefully the discussion following it, are responsible, we presume, for the misinterpretation.

It is obvious from the foregoing résumé that the factor, bright-

[93] Klug, F. Ueber Farbenemfindung bei indirectem Sehen. A. f. O., 1875, $XXI_{,1}$, pp. 274-278.

[94] Chodin, A. op. cit., p. 178.

ness of the stimulus, has been very inadequately treated in the literature. The specific question has never been answered, in fact has never really been investigated: Does the amount of brightness difference existing between the colors influence their limits of sensitivity in the peripheral retina? Aubert[95] and Chodin[96] and others have shown that the sensation limen of color when mixed with white is higher than the limen when mixed with black. This fact may be explained as due to the superior inhibitive power of white. But within what limits this greater inhibitive action of white is sufficient to cause the peripheral limit of a color mixed with white to be narrower than that of an equally intense color mixed with black has not been determined. And certainly it has never been shown that the brightness difference that exists between the standard colors at full saturation exerts an inhibitive action sufficiently strong to cause a change in the peripheral limits. It has never been claimed, for example, that a light color in its state of maximal saturation is more inhibited for sensation than a dark color in its state of maximal saturation by the brightness component inherent in each; in other words, that a saturated yellow is more inhibited by its brightness component than is a saturated blue by its brightness component. In fact, in strange contradiction to this, it has often been held that the colors which have the stronger white component are the more intense. Yellow, for example, has been frequently called a more intense color than blue just because of its proximity to white.

We must conclude, then, that the assumption that color limits must be investigated with stimuli of equal brightness is probably based upon the belief that stimuli differing in brightness differ also in intensity. This belief has doubtless arisen from the fact that as stimuli are ordinarily varied, a change of brightness is accompanied by a change of intensity, and conversely a change of intensity is accompanied by a change of brightness. But brightness and intensity are not inseparable variants. Conclusions should not be drawn, therefore, until the influence of bright-

[95] Aubert, H. Physiologische Optik, p. 532.

[96] Chodin, A. op. cit., p. 183.

ness change has been investigated in separation from intensity change. Since this investigation has not been made, we are forced to consider that the influence of the brightness of the stimulus upon the limits of color sensitivity is at present an open question, despite the verdict to the contrary by Bull, Hegg, Hess, and Baird. We have, therefore, included it in our own work as one of the points to be investigated. The results of this investigation are reported in the experimental section of this paper.

3. *Brightness of the Field Surrounding the Stimulus.*

The recognition of the influence exerted by the field surrounding the stimulus upon the limits of the color zones, has led to the substitution of the campimeter for the perimeter in investigations of the color sensitivity of the peripheral retina. The campimeter provides a means of readily changing the brightness of the field which surrounds the stimulus, so that the effects of these changes may be studied both upon the limens and limits of color and upon the quality changes that appear as the stimulus is carried from the fovea to the periphery.

The influence of the field surrounding the stimulus is twofold. In the first place, it directly modifies the stimulus by contrast induction, provided there is brightness opposition. This effect was observed and to some extent investigated by Aubert and Woinow before the campimeter came into use. In the second place, the campimeter screen, when of sufficient size, stimulates the entire retina uniformly and guarantees an equal brightness-adaptation of every portion. It was the recognition by Krükow[97] that former methods had allowed the retina to become unequally fatigued to chance objects in the surounding room, that led directly to the first use of the campimetrical method of working. Krükow did not, however, study the effect of different backgrounds. He used a uniform gray field to stimulate the surrounding retina, and mounted stimuli on cards of equal quality. In subsequent investigations, a black background was used almost exclusively. So far as induction is concerned,

[97] Krükow, loc. cit.

this screen gives conditions with the light-adapted retina somewhat similar to those existing in dark-room work; that is, in each case the stimuli are lightened by contrast from the surrounding dark field.

Woinow and Aubert worked only with small areas of background and thus secured the given brightness stimulation over but a small zone surrounding the part of the retina stimulated to color. Woinow[98] placed a disc made of black and white sectors behind the stimulus to be investigated. He found that, when the sectors were so adjusted that when rotated they formed a dark gray, the color limits were the same as when the sectors were arranged to give a light gray sensation. From these results, he concludes that the color zones are not influenced by the brightness of the field surrounding the stimulus. Aubert[99] fastened colored paper stimuli on white and on black cards. He found that the black card gave relatively wider limits for red; and that the white card gave relatively wider limits for yellow, green, and blue, except for very small stimuli.

The first campimeter described was apparently what is now called the Hering color-mixer.[100] Hess[101] was the first to employ it for an investigation of peripheral color sensitivity. He and later Tschermak[102] tested by means of it the influence of the brightness of the surrounding field upon the color limits. With this apparatus pigment stimuli are observed through an opening in a large gray screen, placed in the horizontal, which can be turned toward or away from the source of light, and in this way a surrounding field can be obtained that is lighter, darker, or equal in brightness to the stimulus at its point of disappearance as color. Hess and Tschermak both found that the limits of sensitivity to

[98] Woinow, M. loc. cit.

[99] Aubert, H. Physiologische Optik. pp. 541-543.

[100] Titchener in *Experimental Psychology, Instructor's Manual, Qualitative,* 1901, p. 20, ascribes the description of this apparatus to Hering, giving as reference A.f.O., 1889, XXV_4, p. 63. The writer is unable to find any mention of this apparatus in this or any other of Hering's articles. It is, however, described in some detail on p. 25 of the paper by Hess which just precedes and accompanies the Hering article to which Titchener refers.

[101] Hess, C. loc cit.

[102] Tschermak, A. op. cit., p. 561.

color were widest when the surrounding field was equal in brightness to the stimulus. If the stimulus appeared lighter or darker than the surrounding field, the limits were narrowed proportionately to the loss of saturation of the stimulus color due to the action upon it of the brightness quality induced by the background.

Fernald[103] used a vertical campimeter. She summarizes her results with white and black screens as follows: "All the colors except the reds are perceived at a greater angle of eccentricity with the dark than with the light backgrounds."

The only quantitative estimates of the effect of different backgrounds reported by these experimenters is given in terms of the effect upon the color limits. In no case has the amount of white or black induced by a given screen been determined, nor has the effect of the induction upon color sensitivity ever been tested in any part of the retina by the most direct means available, namely, the determination of the limen or threshold of sensation. Neither has any attempt been made to isolate the influence of the background from the influence of the brightness of whatever stimulates the retina immediately before the exposure of the stimulus. This factor, which we shall discuss under the name of *preëxposure,* is effective through the intensive brightness after-image that is set up on the retina and is superimposed upon the colored stimulus when it is exposed. Its importance has never been recognized by previous investigators, nor has its effect ever been studied in isolation from the effect of the brightness of the background. In short, in surveying the literature, one can scarcely help but feel that the study of the influence of the surrounding field has been neither analytic nor systematic.

4. *The General Illumination.*

The effect of the general illumination of the retina on color sensitivity has been recognized since the time of Purkinje and Aubert. It has been studied in some detail by a number of experimenters, among whom may be mentioned Kramer and Wolffberg. Both have shown that the sensation aroused by the colored stimulus is weakened by a reduction of the general

[103] Fernald, G. M. The Effect of Achromatic Conditions on the Color Phenomena of Peripheral Vision. Psychol. Rev. Monog., 1909, X, No. 42.

illumination, but neither, it may be mentioned, has given a method of keeping the general illumination constant. Kramer's[104] purpose was to determine the sensitivity of the eye under different intensities of daylight and artificial illumination. His method was as follows. Stimuli, 4 mm. square, of blue, yellow, red, and green paper on a black background were used. The distance at which the stimulus had to be placed from the observer to be just recognized as colored, was tested by sunlight and when the sky was obscured by clouds and for three intensities of each of the following sources of artificial illumination: candle light, gas, petroleum, sodium, potassium, strontium, and calcium lights. His results may be summarized as follows: (1) Red is seen at the greatest distance in all lights except calcium, in which case green is seen when farther away than red. The other colors are recognized in the order green, yellow, blue. (2) All the colors are recognized at a greater distance when seen by sunlight than when illuminated by artificial light or the dull light from a clouded sky. (3) As the intensity of the artificial illumination is decreased, the colors must be placed nearer the eye to be recognized. Kramer's method of working, however, may be criticized because he ignored the white contrast which the black background induced across the stimuli. The induction across the stimuli whose sizes were only 4 mm. square must have been considerable. It was, moreover, of different amounts in each case; because brightness contrast is greatest when there is maximal brightness opposition. The modification of the light colors, as a result of contrast induction, must, therefore, have been greater than that of the dark colors.

Wolffberg's[105] interest was in the influence of gradual alterations of the general illumination on the light and the color sensitivity of the central and of the peripheral retina. His room was illuminated by daylight entering through a window. Fifteen different degrees of illumination were produced by fastening from one to fifteen thicknesses of tissue-paper over the win-

[104] Kramer, J. Untersuchungen über die Abhängigkeit der Farbenempfindung von der Art und dem Grade der Beleuchtung. Inaug. Diss., Marburg, 1882.

[105] Wolffberg. Ueber die Prüfung des Lichtsinnes. A. f. O., 1887, XXXI., pp. 1-78.

dow. The illumination obtained when the window was uncovered was called 15/15; when covered with one thickness of tissue-paper, 14/15, etc. His method of determining the effect of variations of illumination upon the central retina was as follows: Pigment stimuli were placed at a standard distance of 5 meters from the observer, and the size of stimulus necessary to render it just visible in its true color was determined. In the peripheral retina, he investigated to what extent the limits of white and of colored stimuli were altered by reducing the illumination. In all his experiments, the stimuli were fastened on a black background. Wolffberg's results for the central retina are shown in the following table. The stimuli were circular in shape and of diameters given in columns 2, 3, 4, 5, and 6.

Illumination	Size of Red Stimulus	Size of Blue	Size of Green	Size of Yellow	Size of White
15/15	.5 mm.	3 mm.	3 mm.	1.5 mm.	.2 mm.
14/15	1.5	5	4	2	.5
13/15	2	6	6	4	1.
12/15	2.5	12	12	4.5	2
11/15	3	20	20	5	2.5
5/15	10	50	50	10	6

These results show that in the central retina a decrease of illumination has a greater effect upon the sensation of color than upon the sensation of white. Wolffberg next tested the effect of a gradual decrease of illumination upon the limits of sensitivity to white and to the colors. He found that the extent of the visual field was not narrowed for white when the illumination was decreased to 1/15. The color limits, however, narrowed gradually when the illumination was decreased from 15/15 to 3/15. The narrowing was in no case more than 15°. The relative extents of the fields remained unaltered, that is, the order of size was in every case blue, red, and green.

Although special investigations have been conducted by Kramer, Wolffberg and others to show the effect of changes in the general illumination upon color sensitivity, in general little if any precautions have been taken by earlier experimenters to prevent such changes when investigating color sensitivity. Either the experimenter has not considered the influence of the

general illumination, or he has been satisfied to take the rough precaution to work only on bright days at stated hours. Ole Bull,[106] for example, commented at length on the factor of general illumination, but suggested no method for its standardization. He writes: "The amount and nature of the general illumination are of more significance in perimetrical observations than one is accustomed to consider. It must always be noted whether the sky is clear or cloudy, whether it rains or snows. The extreme limits of the visual field for mixed light undergo such wide fluctuations that it is of little value to establish an average limit on the basis of a number of measurements. Changing illumination, conditioned by the time of day and of year during which the work is carried on, as well as the locality in which it is undertaken, produce variations in the same stimulus large enough to cause differences of from 10° to 20° [in the limit of sensitivity]. Especially in the nasal parts of the retina does the illumination influence the color limits, while their position remains more constant in the temporal retina." Fernald,[107] however, did make some attempt to obtain a standard illumination. She arranged white curtains at the windows of her optics-room which could be lowered on bright days and drawn on dark days. This rather crude method was used also by Thompson and Gordon.[108] It is scarcely necessary to point out that the method lacks the first essential of standardization, namely, a means of measuring.

It is surprising that Wolffberg as the logical corollary of his work, did not draw attention to the importance of standardizing the illumination of the visual field in all work on the color sensitivity of the retina, and show how it could be accomplished by a modification of his method of working. He already had at hand one of the essentials for standardizing, namely, a method of changing the illumination of his room. The other essential, a method of measurement by means of which an illumination could be identified with a previous illumination chosen as standard,

[106] Ole Bull. Perimetrie. Bonn, 1895, p. 8.

[107] Fernald, G. M. Psychol. Rev., 1905, XII, p. 392.

[108] Thompson and Gordon. A Study of After-images on the Peripheral Retina. Psychol. Rev., 1907, XIV, p. 122.

might have been derived from his results. For example, it would seem to have been a simple matter for him to have chosen as standard the particular illumination at which the red stimulus of 2.5 mm. diameter, the blue and green of 12 mm. each, the yellow of 4.5 mm., and the white of 2 mm. were just recognizable at a distance of 5 m. Stimuli of those sizes, it will be seen from the tables, were just recognizable at this distance at the illumination called 12/15, when 15/15 represents the illumination "bei günstige Tagesbeleuchtung." Using this condition as an index of the standard illumination, he could at any time have adjusted the illumination of the room by adding to or subtracting from the layers of tissue-paper covering the window, until the stimuli of these sizes were again just recognizable at the given distance. The accuracy and sensitivity of this method could have been tested by comparing the results of a series of determinations. An accurate and highly sensitive method sustaining some similarity in principle to the method suggested here, will be described by the writer in the experimental part of this paper.

The influence of changes in the intensity of the general illumination upon visual acuity has received some attention from physiologists and oculists. Although their work has no direct bearing on the influence of change of illumination upon color sensitivity, it may be of interest to note briefly their methods of dealing with these changes.

Schweigger[109] in 1876, using the Snellen series of optotypes and the formula $V = \frac{N}{n}$ in which *n* represents the distance of the test-object from the eye of the observer, and *N* the number of the series of the smallest of optotype series that can be recognized at that distance, found that on a clear day his visual acuity equalled 20/15, on a cloudy day it equalled 30/15. To correct for the errors in visual acuity introduced by changes in the illumination he first found the number of the series of the smallest optotypes that he himself could read at a given distance, then he determined this value for the patient at the same distance. Using his own results $V = \frac{N}{n}$ as standard, he determined the ratio of the patient's results $V = \frac{N^1}{n}$ to his own. This ratio $\frac{N^1}{N}$, he considers the expression of what the patient's visual acuity would be at standard illumination.

Cohn's and von Hoffman's interests lay mainly in testing the eyes of schoolchildren and in determining what was the lowest intensity of illumination of the schoolroom suitable for work. Cohn[110] in 1867 and 1883

[109] Schweigger, E. Sehproben. Berlin, 1876, Preface, pp. III-IV.

[110] Cohn, H. Untersuchungen der Augen von 10060 Schulkindern. Leipzig, 1876, p. 101; Hygiene of the Eye in Schools, translated by Turnbull, 1883, p. 131.

claims that as there is no photometer available for the measurement of the intensity of daylight, the eye must be its own photometer. Later in 1892[111] he states that L. Weber has made a daylight photometer, but as this apparatus is difficult of access, he would recommend apparently that the changes in visual acuity experienced by the eye with changes of illumination be used as a means of identifying a given degree of illumination. He endorses von Hoffman's[112] method of accomplishing this. According to this method, Type No. 30 of the Snellen optotypes is placed in the schoolroom 15 feet from the eyes of a child whose visual acuity is 15/15. If the child recognizes the letters of the test, the room is sufficiently well-lighted. Work in the room is to be suspended as soon as the child can no longer recognize the letters of the test. This provided a practical method, not for measuring the illumination of a room, but for detecting when a room has insufficient light for purposes of schoolwork.

Nicati[113] tested the influence of change of the intensity of artificial illumination upon visual acuity. His work was purely quantitative. He proposes a unit of measure by means of which to study this effect. This unit he calls *a photo*. *A photo* is the smallest intensity of light which when placed 1 meter from a test-object printed in black on a white card gives to normal monocular vision a normal acuity. The method of measuring the intensity of an illumination in *photos* is as follows. A source of light is brought towards the test-object until the observer has normal acuity. The intensity of the source then equals as many *photos* as the square of the distance of the light-source from the test-object, measured in meters. Nicati finds that there is an absolute logarithmic relation between visual acuity and intensity of illumination. As visual acuity is decreased in arithmetical series, intensity of illumination decreases in geometrical series. His table showing this relation is as follows:

Visual Acuity	1	.9	.8	.7	.6	.5	.4
Distance of source	1*M*		2*M*		4*M*		8*M*
Intensity in *photos*.	1	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{8}$	$\frac{1}{16}$	$\frac{1}{32}$	$\frac{1}{64}$

Since this relation exists, either the intensity of illumination can be con-considered a measure of visual acuity, or visual acuity can be considered a measure of the intensity of illumination. That is, the scale of visual acuity is a photometric scale and can be used as such. To measure the illumination of a room in *photos,* then, the visual acuity should be determined in different portions of the room, and the average of the *photos* corresponding to these values in the acuity scale be taken as the measure of the illumination of the room in *photos*. The method as formulated is apparently serviceable as a means of estimating the illumination of a room chiefly, if not entirely, when it is below what is needed for normal acuity of vision.

[111] Cohn, H. Lehrbuch der Hygiene des Auges. Wien und Leipzig, 1892, pp. 34-35.

[112] von Hoffman, H. Augenuntersuchungen in vier Wiesbadener Schulen. Klin. Monatsbl. f. Augenheilk., 1873, pp. 289-290.

[113] Nicati, W. Physiologie Oculaire humaine et comparée normale et pathologique. 1909, p. 163ff.

B. METHODS OF STANDARDIZING THESE FACTORS.

1. *Size of the Stimulus.*

No special method of standardizing the size of the stimulus is required. Each experimenter who has recognized it as a factor has chosen what he considered the most favorable area to work with, and has used that area in all of his comparative determinations. No limitations as to area have been prescribed other than that it must not be too large nor too small.

2. *Intensity of the Stimulus.*

As a general introduction to our discussion of the methods that have been used to standardize the influence of intensity, we wish to call attention once more to the fact that in no one of these investigations have the stimuli employed been equated with regard to the energy of the light given to the eye, nor have they been standardized in terms of any fixed unit of intensity that can be compared; and that until this is done, we have no proper means of determining the comparative limits of sensitivity to the different colors; nor of determining and expressing the comparative limen or j. n. d. of sensitivity. For example, attempts to determine the relative sensitivity of the retina to the four principal colors have been made among others by Aubert, Chodin, Raehlmann, Butz, Lamansky, and Dobrowolsky: also by Bull, Hess, Hegg, and Baird. As stated above, however, these experimenters did not equate their stimuli with regard to the energy of light given to the eye for the investigations of the limits of sensitivity nor estimate sensitivity in terms of a common unit for the work on limens and j. n. d.'s of sensitivity. The last four, however, did attempt to equate in intensity, but the equation was made in terms of a subjective measure arbitrarily selected, namely, the proportion in which the pairs of antagonistic colors must be combined to produce gray, or, in terms of the Hering theory, to cancel each other.

At this point, two general criticisms may be passed on this method of equating. (*a*) The stimuli should not be equated in terms of any subjective measure if one is to test the comparative sensitivity of the retina to the different colors. This begs

the question at the outset. If, for example, a direct judgment of the intensity of the sensations aroused by two stimuli either at the limen or higher in the intensity scale be taken as the criterion for determining their equality, the method begins by making the stimuli of such physical intensity that they are sensed equally. In no fashion could the comparative sensitivity of the retina to the colors in question be determined by such stimuli. Suppose, for example, the limits of sensitivity of the peripheral retina were to be investigated, and for this, the stimuli which had been made subjectively equal for the central retina were used, the results obtained would not at all express the comparative limits for the colors in question. If these limits should be found to coincide, the conclusion could not be drawn either that the sensitivity of the retina to these colors extended only to this point, or that there was equal sensitivity at this point to the colors used. At most no more could be said than that approximately the same ratio of sensitivity to the two colors obtained in this region that was present at the point in the central retina for which they were equated; but this ratio may not be a 1:1 ratio. In fact, the investigator who gets his limits to coincide with stimuli so equated finds himself in the somewhat ludicrous position of having made his conditions such that the limits could not help but coincide, regardless of whether they actually ought to do so or not. He is not working with real limits, but with limits arbitrarily established, and the coincidence he finds is not a fact, at least not so far as he is able to determine by his method of working, but an artifact. To illustrate, the retina might be much more sensitive to red than to green; but if the red stimulus were reduced in physical intensity until the sensation it aroused was equal in intensity to the sensation aroused by the green, it is obvious that the comparative sensitivity to these colors could not be directly tested at any point. The limits of the red zone so determined might, for example, coincide with the limits of the green zone, although the extent of the red zone would have been much wider had stimuli of equal physical intensity been used. So much may be said for this as a type of subjective measure of equality, and what is said in criticism of its use for

investigating the comparative sensitivity of the retina has a general application to all subjective measures.

(b) The stimuli, especially should not be equated in terms of the cancelling power of antagonistic colors.[114] This method is analomous. One scarcely knows what it does accomplish. On the one hand, stimuli so equated are in no way equated in physical intensity; and on the other hand, it would be the merest assumption to say that they have equal power to arouse sensation. To demonstrate this, let us compare certain colors with regard to their comparative power to arouse sensation and to cancel each other. There are three ways by which we may judge the power of a color to arouse sensation:— (*a*) the value of its limen when mixed with a gray of equal brightness; (*b*) the value of its j. n. d. at different points in the intensity scale; and (*c*) the direct or introspective judgment of its intensity. Estimated in all of these ways, spectral red, as prepared in pigment colors by Maxwell after Helmholtz, has greater power to arouse sensation than the green of the series. And yet on the color-mixer, it requires 240° of this red to cancel or obliterate all trace of 120° of the green. And if sufficient blue be added to the mixture to give gray, the proportions of red and green are 165° and 115° respectively. Thus, whether the result of the combination is yellow or gray, the red stimulus, although it has the greater power to arouse sensation, is required to be in considerable excess of the green. We regret that we can not make a similar comparison for the blue and yellow of the Maxwell series, because we were unable to procure them in season for this work. But using the blue and the yellow of the Hering pigment papers, we find that this blue has a lower limen in a gray of its own brightness than the yellow has in a gray of its brightness, and that introspectively it is judged much more saturated than the yellow. And still at the general illumination we have chosen as our standard, 200° of blue are required to cancel 160° of yellow.[115]

[114] There are problems in the optics of color in which subjective equations of intensity may be desired. For a description of what the writer considers a proper method of making the subjective equation, see this paper p. 83, footnote.

[115] If the illumination is decreased, we find that a different proportion

In a later paper, we shall show that if the complementary colors can be assumed to cancel each other, because a certain amount of the one when combined with a certain amount of the other, kills it for sensation, then, by the same token, the non-complementary colors may be assumed to exercise a degree of this cancelling action. For a definite and considerable amount of each must be mixed with any other before it is sensed, the amount required varying over a wide range when one of them is combined with each of the others in turn. We may draw upon the non-complementary colors, then, for a further demonstration of our thesis that the cancelling power of colors upon each other is no measure of their power to arouse sensation. A notable instance of this is the combination of red and yellow to give orange. Working with the Hering pigments, we find that the standard orange of the series, judged as sensation, seems to be equally red and yellow. The standard red of the series, however, which is chosen to form the orange, has greater power to arouse sensation than the yellow by all of the tests mentioned above. Still 295° of red are required to be combined with 65° of the yellow to give the orange which as we have said is equally red and yellow as sensation. Orange furnishes us with only one instance of the non-equivalence of cancelling power to sensation-arousing power that may be found among the combinations of non-complementary colors.[116]

We must, then, conclude that even if one were to err so profoundly as to choose a subjective measure for equating the intensity of his stimuli for an investigation of the comparative

is required to produce cancellation. This difference depends upon the fact that colors do not lose their saturation with equal rapidity with decrease of illumination. The dependence of cancelling proportions upon the general illumination may be pointed out as a minor source of error in the use that has been made of this method by investigators who have conducted their experiments in daylight, for they did not work at an invariable or standard illumination.

[116] In the above demonstration that cancelling power can not be taken as the equivalent of sensation-arousing power, we have assumed that we have not left our work open to criticism in the use of pigment instead of spectral colors, or even in passing from one series of pigment colors to another, because in each case, our test of the cancelling power and of the sensation-arousing power was made with the same stimuli.

sensitivity of the retina to the different colors, this measure should not be selected in preference to the power to arouse sensation as determined either by limen tests, by direct introspective judgments of intensities, nor by the j. n. d. method described on p. 83 footnote. One can only surmise the following reasons for the selection. (*a*) The limen and the just noticeable difference tests, either of which is a proper method of estimating the power of a stimulus to arouse sensation, were probably not taken into consideration at all. The alternative test, the introspective judgment of equal intensities, is difficult to make. And the method given on p. 83 footnote, which is preferable to any method known to the writer for subjectively equating stimuli of all degrees of intensity, has never been suggested even in principle prior to the publication of this paper. It may have been thought that equality based on cancelling power could be substituted for the equality as determined by the other methods.

The reason for selection of equation in terms of cancelling power is not stated by any one of the four men who has made this selection. Considering the statement of each in turn, we find that Bull who wished to obtain color stimuli of equal saturation and brightness, merely states that he does this by establishing pairs of colors such that equal amounts of each cancel and give a gray that conforms to the standard gray he has chosen (A. f. O., 1881, XXVII., p. 95). Hess, aiming to obtain a red light such that its red *Valenz*, or, as he says, its capacity to arouse red sensation, is equal to the green *Valenz* of a green light, writes: "Als Nächstliegende erscheint es nun, einem roth- und einem grün-wirkenden Pigmente den gleichen Roth und Grünwerthe dann zuzuschreiben, wenn dieselben zu gleichen Theilen eine farblose Mischung geben" (A. f O., 1889, XXXV., p. 39). Hegg wishing to equalize the color-values of his stimuli, claims that this is possible for only the two members of each pair of antagonistic colors. Red can be made equal in color-value to green, he says, or yellow to blue, but green and blue can not be equalized. He continues: "Wir betrachten ein *Roth* und ein *Grün* als chromatisch äquivalent, wenn sie auf der Rotationsscheibe zu gleichen Theilen gemischt sich gegenseitig total aufheben, so dass eine Mischung entsteht, welche weder ins rothliche noch grünliche sticht." (A. f. O., 1892, XXXVIII., p. 149). Baird offers no reason whatever for selecting the method of cancelling power by means of which to equate color-values. He apparently takes for granted that this method is the only one, and does no more than describe how the method was applied to his particular stimuli.

The search for a reason for this selection may, however, be pushed back a little further. We find that in 1880 before any of the work mentioned above was published, Hering (Lotos. Jahrbuch für Naturwissenschaft,

1880, I, pp. 76-107) had made statements from which we can conclude that in his opinion two antagonistic colors of equal sensation-arousing power cancel. Hering's statements leading to this conclusion are as follows: (*a*) "Die Vermögen der Lichtstrahlen, die weisse Empfindung zu fördern, will ich die weisse Valenz der Lichtstrahlen nenne." (p. 79.) (While this definition is not specifically repeated for colored light, still it is obvious from the text that it applies to colored as well as to white light).[117]

[117] The following quotations are appended to show the use of *Valenz* by Hering and Hess:

Hering (Zur Erklärung der Farbenblindheit aus der Theorie der Gegenfarben. Lotos—Jahrbuch für Naturwissenschaft, 1880, I., p. 76-107) writes (p. 79): "Die Vermögen der Lichtstrahlen, die weisse Empfindung zu fördern, will ich die weisse Valenz der Lichtstrahlen nennen.

"Die Grösse dieser Valenz ist offenbar von zwei Factoren abhängig: ersten von der objectiven Intensität oder lebendigen Kraft, mit welchen die Strahlen verschiedener Wellenlänge bis zur empfindlichen Netzhautschicht gelangen, und zweitens von dem, was wir die specifische weisse Erregbarkeit des Sehorgans gegenüber den Strahlen verschiedenen Wellenlänge nennen, d.i. das Vermögen dieses Organs, unter dem Einflusse jener Strahlen die Weissempfindung deutlicher werden lassen.

"Ausser der weissen Valenz, welche allen Lichtstrahlen gemeinsam ist, kommen nun den einzelnen Strahlenarten verschiedene farbige Valenzen zu. Allen Strahlen vom aussersten Roth oder vom Anfange des Spectrums bis zu jenem im Tone reinen Grün, welches eine Gründfarbe ist und welches wir das Urgrün nennen wollen, haben eine gelbe, allen Strahlen vom Urgrün bis zum violetten Ende des Spectrums eine blaue Valenz."

Hess (Ueber den Farbensinn bei indirectem Sehen, A. f. O., 1889, XXXV., pp. 1-60.) writes (p. 30): "Unter weisser Valenz eines farbigen homogenen oder zusammengesetzten Lichtes versteht Hering den Helligkeitswerth desselben für eine Netzhautstelle, welche das farbige Licht wegen mangelhaften Farbensinnes oder aus anderen Gründen farblos sieht" (p. 39): "Um über das gegenseitige Verhältniss der Abnahme der Empfindungsvermögens für Roth und Grün, resp. Blau und Gelb überhaupt Untersuchungen anstellen zu können, ist es zunächst erförderlich, für beide Arten des Empfindungsvermögens ein gemeinsames Maass zu finden. Verschiedene grüne Lichter besitzten die Fähigkeit, grüne Empfindung zu erzeugen, in sehr verschiedenem Maasse, sie sind, um es kurz zu bezeichnen, sehr verschieden grünwirkend. Das mehr oder minder grosse Vermögen eines Lichtes, grün zu wirken, bezeichnen wir mit Hering als die grüne Valenz oder den Grünwerth des bezüglichen Lichtes". (p. 40): "Bestimmen und messen lässt sich derselbe nur in Bezug auf ein als Normalgrün gewahltes Pigment, welches unter genau denselben Beleuchtungsverhältnissen wie das zu untersuchende gesehen wird. Ganz analoges gilt von dem Roth-, Gelb-, und Blauwerthe eines Pigmentes.

"Für die vorliegende Frage handelt es sich aber nicht bloss darum die Grünwerthe oder die Rothwerthe verschiedenen Pigmente je unter sich zu vergleichen, sondern den Grünwerthe eines grünwirkenden mit dem Rothwerthe eines rothwirkenden Pigmentes.

"Als das Nächstliegende erscheint es nun, einem roth- und einem grünwirken-

(*b*) "Zwei homogenen Lichter, nun, von welchen das eine ebenso gelb (oder roth) wirkt, und das andere blau (oder grün) so dass beide Valenzen sich aufheben, nenne ich gegenfarbig äquivalent" (pp. 83-84). In the first of these statements he directly calls the capacity of a color to arouse sensation its *Valenz*. And from the second it may readily be derived that when the yellow-sense, for example, is affected as strongly by yellow light as the blue-sense is affected by blue light, complete cancellation will ensue,—that is, equality in cancelling power may be considered as the equivalent of equality in capacity to arouse sensation. In making this deduction we have of course assumed that *wirkt* refers to sensation-arousing action and not to cancelling action. We have no doubt that this assumption is correct, still it may be worth while to bring forward direct evidence in support of this point from a statement made by Hess while working under Hering's direction. Hess writes: "Das mehr oder minder grosse Vermögen eines Lichtes grün zu wirken, bezeichnen wir mit Hering als die grüne Valenz oder den Grünwerth des bezüglichen Lichtes" (op. cit., p. 39). Here *Vermögen grün zu wirken* is made the equivalent of *Valenz* and *Valenz* by definition is the capacity of a color to arouse sensation. Hence we have little hesitation in assuming that in the case in question *wirkt* also refers to the sensation-arousing action of the colored light and not to its cancelling action, and in concluding, therefore, that Hering believed that antagonistic colors of equal power to arouse sensation would also have equal power to cancel each other. Since this is true, it is probable that the followers of Hering (Hess and Hegg) assumed the equivalence of power to arouse sensation and power to cancel and equated their stimuli accordingly. That Hess was actuated by some such reason is shown by a statement made by him in his discussion of this point. He writes: Die von Herrn Professor Hering angegebene, oben geschriebene Untersuchungsweise gestattet mit grosse Genauigkeit den zu vergleichenden Pigmenten gleich grosse farbige und gleich grosse weisse Valenz zu geben, sie ermöglicht es, für die Werthigkeit der Farben einen genauen numerischen Ausdruck zu winnen und in die Rechnung einzuführen" (op. cit., p. 58). Hegg also seems to refer back to Hering, for he uses the Hering terminology in discussing the equation of his stimuli.

Or (*b*) since cancellation is the corollary to the assumption of an assimilation-dissimilation mechanism, it may have been considered for some reason, not readily understood by the writer, that an equation based upon it is the proper one to make.

Having said this much about the impropriety of selecting a subjective measure for the intensity equation of stimuli, let us

den Pigmente den gleichen Roth-und Grünwerth dann zuzuschreiben, wenn dieselben zu gleichen Theilen, z.B. auf dem Kreisel gemischt eine farblose Mischung geben, im Falle sie dazu aber in einem anderen Verhältnisse gemischt werden müssen, anzunehmen, dass sich der Rothwerthe des einen zum Grünwerthe des anderen umgekehrt verhält wie die Grösse der beiden zur Herstellung einer farbosen Mischung nöthigen Sectoren."

pass to a résumé of the attempts that have been made to apply this measure by Bull, Hess, Hegg, and Baird. Hegg selected four stimuli that suffered no alteration of color tone in passing from the center to the periphery.[118] These were a bluish-red, a bluish-green, a blue, and a yellow. They were equated in pairs, the bluish-red to the bluish-green, and the blue to the yellow, as follows. It was determined in what proportions the members of each pair had to be combined to produce gray, and from these proportions, values of the sectors of the stimulus disc were calculated for each color. The procedures of Bull and Hess were essentially similar..

Baird, employing the light transmitted by gelatines, prepared blue, yellow, red, and green stimuli as follows. A lantern containing an incandescent lamp of 16 candle-power was used as source of light. The stimulus light was emitted from the lantern through a circular aperture, 15 mm. in diameter. Gelatines were placed over the aperture in combinations which gave the four stable colors, and their spectral values were obtained. A disc in which two windows of equal size had been cut, was rotated on a motor in front of the lantern. The combination of gelatines to give the red stimulus was fastened across one of the windows, while the green combination was used to cover the other window. As the windows were of equal size, the rotation of the disc gave a mixture which contained equal proportions of both stimuli. The gelatine combinations were changed by adding, subtracting, or substituting until the mixture showed no trace of color. Similar equations were obtained for the blue and the yellow stimuli.

It will be seen from the work of these men that even if their methods had been based upon a proper principle of equating, they would not be adequate for all that is involved in the problem

[118] Only one meridian was used for determining this invariability of color tone. It is obvious that a conclusion should not be drawn from such a scant investigation of the sensitivity of the retina. For example, working with the red, green, blue, and yellow of the Hering standard papers, the writer has found that with a careful standardization of factors, an investigation in any considerable number of meridians shows that stability of tone is possessed by the blue alone.

of determining the comparative sensitivity of the retina to the different colors. For not only is the comparative sensitivity to the complementary colors desired, but to the non-complementary colors as well. The method offers no possibility, for example, of equating red and green to blue and yellow. One can only conjecture how much of our present conception of the comparative extent of the different zones of color sensitivity is an artifact due to the use of stimuli that have not been equated with reference to the energy of the light-waves they give to the eye. In addition, then, to the objection that the methods that have been used thus far to equate the color stimuli in intensity are found to be essentially wrong in principle, the further criticism may be offered that they are not adequate in scope. An energy equation of the light-waves by means of some radiometric device, for example, the thermopile, the bolometer, the selenium cell, or what not, alone seems adequate to the requirements set by the problem of determining the comparative sensitivity of the retina to the different colors, or the comparative limits of the zones of sensitivity.

Energy equations in terms of radiometric units have been made by Langley and Pfund, but up to this time no investigation of color sensitivity has been made with colors equalized in energy. Langley[119] invented the bolometer and determined by means of it the relative distribution of energy in the normal spectrum. In order to equalize the energy of the different colors, he states that one may vary the width of the collimator-slit until equal radiometric readings are obtained. In his own experiments on visual acuity, he does not, however, proceed in this way. Tables of logarithms were illuminated in a dark-room by monochromatic light representing known amounts of energy. The greatest distance at which the figures could be read was determined for each of the colors, and corrections were applied for inequalities in the energy of the different lights. The corrections were made in terms of the distribution obtaining in the following table.

Pfund used the first method suggested by Langley. In an

[119] Langley. Energy and Vision. Amer. Journ of Science, 1888, XXXVI., 3rd Ser., pp. 359-379.

investigation of the changes in the resistance of selenium to lights of varying wave-length, he employed differently colored

Wave-length	μ .35	μ .38	μ .45	μ .50	μ .55	μ .60	μ .65	μ .70	μ .75	μ .768
Heat	1.8	5.3	11.9	17.3	20.7	21.9	22.2	21.4	20.7	20.2

beams of equal intensity. The intensity equations were made as follows. Using first a Rubens thermopile[120] and later a radio-micrometer,[121] Pfund determined which wave-length gave the least galvanometer deflection. He then reduced the more intense beams by interposing a smoked wedge of the proper thickness until every portion of the spectrum produced the same deflection. In this way he obtained colored lights of known and constant energy.

Psychological investigators have been slow to recognize the importance of standardization of intensity in radiometric terms of the colors which are to be used for the investigation of sensitivity. The only equations of intensity have been made in subjective terms, a procedure which if done by a proper method may be legitimate for work on certain points relative to existing color theories, but which is not adequate (see this paper, pp. 64-65) to meet the requirements of the problems which deal with the comparative sensitivity of the retina to the different colors.

Note.—Since the completion of this paper, the report of Watson and Yerkes concerning methods of studying vision in animals has been published (Behavior Monographs, 1911, I, pp. 1-89). For the measurement of the intensity of the stimulus they find two methods available, photometry and radiometry. They write: "The method of photometry in all its forms is dependent upon the visual capacity, training, and the special skill of the observer who attempts to use it. For this reason, and others only less important, it is usually desirable to supplement photometric measurements of photic stimuli by measurements of their value in terms of energy. Hence the pertinence of physical measurements. Determination of the value of photic stimuli in terms of heat units by radiometric procedure has proved feasible. Radiometry yields a measurement which is relatively independent of the visual peculiarities of the observer, and it therefore supplements in an invaluable manner the results of photometry" (p. 11).

The authors in question then decide in favor of radiometric measuremen

[120] Pfund, A. A Study of the Selenium Cell. Philos. Mag., 1904, VI Ser. 6, p. 26.

[121] Pfund, A. The Electrical and Optical Properties of Metallic Seleniu Phys. Rev., 1909, XXVIII, p. 326.

and control of the stimuli to be used in determining the animal's color sense. Their reasons for this decision are not, however, those stated in the above criticism of subjective methods of equation either by cancelling power or by sensation-arousing power, namely, that these methods are essentially wrong in principle for tests for the comparative sensitivity of the eye to different colors. That they do not consider them wrong in principle for work of this kind is shown in fact by their recommendation of the Hegg colored papers. The colors of the Hegg papers are equated in intensity in terms of the cancelling power of the complementary colors, the worst of the subjective methods discussed. They write: "These [the Hegg papers] are mixtures of oils on paper yielding the hues red, yellow, green, and blue. These hues are claimed to be equal in intensity and saturation for the human eye. The set is useful as a means of ascertaining, in a preliminary survey, whether an animal readily discriminates two hues which for us are of nearly the same intensity and saturation" (p. 32). It is obvious also that they do not consider the photometric method of equating intensities (also a subjective method) wrong in principle. The method is not recommended merely because it depends upon the visual capacity, training, and special skill of the observer. But the fact that they endorse this method to supplement the radiometric procedure or rather, as quoted above, the radiometric to supplement the photometric shows that they do not realize the absolute diversity of the photometric and of the radiometric curve. Their conclusion, then, in favor of the method of radiometry for measuring the intensity of the stimulus is based upon very different arguments from those which have governed the similar decision reached in the above discussion. They do not seem to entertain any criticism of the subjective method of equating, either the method which measures cancelling power, or the method of photometry, nor do they recommend that either be discarded. Their choice of energy measurement is due largely to the fact that they wish a method which is as free as possible from subjective errors.

3. *Brightness of the Stimulus*

The same investigators who sought to obtain stimuli of equal intensity, attempted also to equate these stimuli in brightness. This may be done in two ways: the white-values of the colors as they appear in direct vision may be equated, or the white-values as they appear in indirect vision may be equalized. The first method was used by Bull who made direct comparison judgments of the relative brightness of the colors, facilitating his comparisons by the use of intermediate color-tones. For example, a blue was changed in brightness until it appeared as light as a given blue-green. Green was then made equal to the blue-green; yellow-green to the green; yellow, to the yellow-green, etc. Hess, Hegg, and Baird employed the second

method. The stimuli were carried to a point in the field of the peripheral retina at which they appeared colorless and their brightness values were altered until the gray sensations obtained from all the stimuli were equal.

Hegg, who used pigment colors, observed the stimulus through an opening in a gray screen, whose brightness could be altered by turning it toward or away from the source of light. He adjusted the screen so that its brightness was the same as that of the gray sensation aroused by the green stimulus in the peripheral retina. Retaining this setting of the screen, he replaced the green by the red stimulus, the intensity of which he had previously equated to the intensity of the green by the method described and criticised in the preceding section. The red stimulus, which was composed of 216° of red, 55° of blue, 89° of white, when observed in the extreme periphery, was seen as a gray that was lighter than the screen. To make the stimulus and the screen of equal brightness, 5° of the white sector had to be replaced by black. A complication arose when blue and yellow were equated to this brightness, resulting from the changes in color-tone which took place. Hegg found that when he added white to lighten the blue stimulus, a sensation of reddish-blue was aroused. (Chodin, it will be remembered (see p. 45), saw in this fact an argument against the possibility of equating the brightness of colors for investigations of this kind.) To cancel this effect, he added green. The addition of black to yellow, which was necessary in order to equate the brightness of yellow to green, resulted in a greenish-yellow sensation. To this he added red in a sufficient amount to cancel the greenish appearance of the fusion.[122]

[122] In connection with a study (done in cooperation with Dr. C. E. Ferree) to determine the physiological level at which the fusion of colored with colorless light sensation takes place, the writer attempted to add sufficient red to cancel the green in a mixture of yellow and black. A curious paradox was observed. Starting with 55° of yellow, and 305° of black, and keeping these proportions relatively constant while red was being added to the mixture, it was reported by a number of observers that, after the addition of about 10° of red, it was seen in the mixture with the green. As more was added, the green and red continued together in varying proportions, until, with about 45° of red in the mixture, it dominated the fusion, which was seen as a dark brownish-orange. Our ob-

Hegg does not give the proportions of the final white-green-blue *Urblau* and the black-red-yellow *Urgelb* which, he claims, were equal in brightness to the *Urroth* and *Urgrün*.

Baird also used the method of indirect vision comparison. The two stimuli to be equated were placed one above the other at a point at which both appeared colorless in the periphery of the retina. The brightness of blue was chosen as standard, and the red, green, and yellow stimuli were darkened to equal it by rotating an episcotister in front of each of them in turn. The sectors of the episcotister were adjusted so that each stimulus was darkened as much as necessary to cause the colorless sensation aroused by it in the periphery to be the same as was aroused by the blue stimulus. Baird does not say that his work was complicated by changes in color-tone. His method would at first glance seem to be more simple than that of Hegg. When, however, we remember that the equation of brightness and apparent intensity had to be carried on hand in hand, we see some of the difficulties he must have encountered. His problem, was to bring the complementary colors to such intensity, that 180° of one cancelled 180° of the other; and at the same time, to maintain them all of the brightness of the blue. But it is apparent that by his method of equating in brightness, an alteration in the amount of colored light coming to the eye is produced every time a change in brightness is made. And as the brightness of the several stimuli had to be changed by unequal amounts to bring them all to the brightness of blue, the amount of colored light coming to the eye was also changed by unequal amounts. This much of the procedure is sufficient to show the difficulty that confronts the experimenter. To equate either for brightness or cancelling power, disturbs the equation established for the other; that is, when the stimuli are brought to equal brightness, their cancelling power will no longer be equal, and *vice versa*. It is obvious that

servation has been verified too many times and by too many observers for us to question its validity. It stands, then, in direct contradiction to Hegg's claim that a change in color-tone produced by altering the white-value of a color can be remedied by adding the complementary color to the stimulus. The difficulty then, seems insurmountable, and stands as one of the objections to the attempt to equate colors in brightness.

the goal desired, if it can be attained at all, must be reached by a series of approximations; and that in the end the experimenter will have very much altered stimuli. Since to equate for both at once, involves making much more radical changes in the stimuli than to equate for one alone, it is plain that in doing both, we but add to the objections we have already made when each is done alone.

It is to be deplored that Baird does not tell us just how he worked in this most difficult part of his technique. The defect is serious, for as the report of his method stands, one can neither pass judgment on its adequacy, nor be sufficiently guided by it, should one attempt to repeat the work. Of the technique that is described, however, the following criticism may be offered. In the equation of the brightness of two stimuli, Baird carried them to an angle of excentricity, at which both appeared colorless. Now, it is seen from his tables, that the limit of blue is some 15° wider than that of green. He has, then, either to show that the brightness of green is the same at its limit as it is 15° peripheralwards, or to equate the brightness of the colors at their individual limits by some means, such as the flicker method.

Since Bull equated his stimuli by the direct vision method, and Hess, Hegg, and Baird by the indirect vision method, a word may be said in concluding this topic with regard to which is the proper method. Obviously, the decision rests upon whether or not the colors have different relative white-values at center and periphery. That they do has been reported among others by Tschermak,[123] and we have been able to confirm this statement. The equation should, therefore, be made in the peripheral retina. As we shall show in the experimental section of our paper, however, no equation should have been made by any of these men for the work they were doing, because unless the stimuli used are extremely weak in saturation, to equate in brightness for the investigation of the limits of sensitivity not only is unnecessary, but results in positive harm. If, however, in other work in the peripheral retina the need for equating should arise, the writer would urge not only that the equation should be made in the

[123] Tschermak, A. op. cit., pp. 564-575.

peripheral retina, but that it should be obtained at the point at which the investigation is to be made.

c. Summary.

With regard to the attempts that have been made to standardize, the results of our historical survey are found to be largely destructive in character. They show, however, that a decided need for standardizing has been recognized. This in itself was a first step in the right direction. The following factors have been discussed: (*a*) *The size of the stimulus.* This factor has been the most adequately treated by previous investigators. Its influence as a factor has been shown, and with it the need of careful measurement of the actual size of the stimulus and of its apparent size as determined by its distance from the eye of the observer. There is still need, however, for further work. While it has been generally held that an increase in the area of the stimulus functions in some degree as the equivalent of an increase in intensity, and thus influences the limits and limens of color sensitivity, no quantitative estimate has been made of the degree of this equivalence. Exact knowledge of this point is not only of general interest in psychological optics, but it is needed in turn in certain problems of standardizing. For example, it is often required that the size of the stimulus be varied and its intensity for sensation be kept constant. This can be done only when the ratio of equivalence is known. As stated on p. 6, this ratio is now being worked out in this laboratory. The results will be reported later.

(*b*) *The intensity of the stimulus.* The influence of the intensity of the stimulus upon color limens and color limits has been pointed out, but no adequate standard of measure has been employed. In dealing with the comparative sensitivity of the retina to the different colors, estimated in terms of the limits, it is obvious that equal amounts of light should be used. Estimated in terms of the limens, the amounts used should be determined in terms of units that can be compared. The problem of the measurement of these amounts of light is wholly physical, hence the standard of the physicist should be adopted. The determination should be in terms of energy as measured by the bolometer,

the thermopile, or other radiometric device. Only in this way so far as we know, can the retina's sensitivity to the different colored lights be obtained in terms of units that can be compared.

(*c*) *The brightness of the stimulus.* Brightness and intensity have been much confused in the literature of the subject. The effect obtained by varying both factors has often been attributed to change in brightness alone. The effect of change in brightness has never been investigated in isolation. This factor, then, occupies the novel position of having been standardized for work on the limits of color sensitivity before the need for such control has been shown.

(*d*) *The preëxposure.* Only in a very general way has the effect of the brightness of the preëxposure been recognized, and the precise reason for its influence has been very little understood. No quantitative estimate of the effect has been made, and no attempt at standardization has been undertaken which has shown any comprehensive knowledge of how the factor works.

(*e*) *The field surrounding the stimulus.* Considerable attention has been given to this factor. A small amount of qualitative work has been done, and some attempts have been made to secure control of the factor. More detailed knowledge, however, is needed of its influence, quantitative and qualitative, over a wider range of the retina. Especially should its relation to general illumination be studied. Until this relation is understood and some means is taken to render the general illumination constant, no effective estimation of the influence of the brightness of the surrounding field can be obtained, nor can it be eliminated as a factor from the color observation.

(*f*) *The general illumination.* The influence of the illumination of the visual field on color sensitivity has been recognized and rough attempts have been made to determine the amount of this influence. The different ways in which changes in general illumination affect color sensitivity have not, however, been determined, and the relative importance of each has not been estimated. Very little attempt at standardization has been made because the first essential of standardization, namely, a sensitive means of measurement, has not been had.

III. EXPERIMENTAL.

A. Purpose of Investigation.

The purpose of this investigation includes the following points. (1) The color observation will be analyzed for the brightness factors that influence its results. (2) A systematic study will be made of these factors with special reference to the determination of their effect upon the color sensitivity of the retina and upon the limits of sensitivity to different colors. (3) It will be ascertained whether the effect of these factors can not be explained in terms of the action of brightness upon color in the peripheral retina and of the rapidity with which the sensitivity to color decreases from the fovea outwards. (4) Methods will be devised to standardize these factors in so far as our results show the need of standardization. No attempt will be made at this point to study the factors that pertain to the source of light with the following exception. Brightness will be isolated from intensity and the effect on the limits of sensitivity of changes in the brightness of the stimulus, made without altering the amount of colored light coming to the eye, will be determined in order to find out whether or not colors should be equated in brightness when the limits of sensitivity are investigated. Moreover, since our problem is concerned only with the brightness factors that influence the action of the colored stimulus upon the retina, the writer will not feel obliged to concern herself with the standardization of her stimulus with regard to either quality or intensity any further than is needed to show the effect of the brightness factors upon the retina's response to these stimuli. All the standardization that is needed will be accomplished by using the same stimulus for all observations the results of which are to be compared; that is, no comparisons will be made except of the effect of the different brightness factors upon the same stimulus. For obtaining results so purely comparative the standardization afforded by pigment papers should be adequate, provided a standard illumination can be obtained so that the amount of

colored light reflected from the pigments will be constant from test to test. Since we were able to secure a highly sensitive means of duplicating our illumination from observation to observation, the standardization of the stimulus afforded by the Hering pigment papers has been considered adequate. More especially has this degree of standardization been considered adequate because the results are to be used primarily merely as a guide in the formulation of a method of working. Having secured a method of working, however, that will permit of a close duplication of results from observation to observation with the pigment papers, the writer will attempt to adapt the method to work in which the colors of the spectrum are used. In order to do this, the following requirements will have to be met. (1) A spectroscope will have to be devised by means of which the retina can be stimulated at any degree of excentricity in any meridian that is desired, for example, a spectroscope that can be used in conjunction with the rotary campimeter[1] in all its adjustments. Such a spectroscope having all the freedom of movements of its parts needed for use with the rotary campimeter has been devised in this laboratory and is now under construction. (2) In order that the stimulus-opening in our campimeter be filled with light sufficiently homogeneous for our purpose, a prism of high dispersive power will have to be procured for use in our spectroscope. A compound prism of the Cassie type[2] seems adequate for this requirement. Such a prism constructed to our special order is now being made for us in Germany. (3) In order that the light may undergo high dispersion and still be sufficiently intense for work in a room lighted to the degree that some phases of our problem demand, a source of light of high intrinsic brilliancy is needed. Constancy in candle-power should also be had. A high voltage Nernst filament seasoned for 100 hours or more and operated on a steady circuit will give, the writer believes, the intensity and constancy required.

Having completed our work of standardizing the factors extraneous to the source of light, an attempt will next be made

[1] For a description of the rotary campimeter see this paper p. 87 ff.

[2] Cassie. Philos. Mag., 1902, III. Ser 6., p. 449.

to secure a better control of the source. Standardization up to the present can be considered successful only with regard to the quality of light. No adequate work has been done on the standardization of the quantity of light for work on color sensitivity. As stated earlier in the paper, the writer believes that this can be done only by means of energy determinations. She expects to do her radiometric work by means of a surface thermopile (Coblentz model)[3] and a DuBois-Rubens *Panzergalvanometer,* unless future results show that some other combination of radiometer and galvanometer is more satisfactory.

Finally from the work of standardization it is our hope to return to the investigation of the problems which we were in the beginning forced to abandon because the work could not be satisfactorily done by the methods now in use in the optics of color. A brief statement of the plan of our future work has already been given in an article published in conjunction with Dr. Ferree in the American Journal of Psychology.[4] In order that the scope of this work be known at this point, and that the importance of the present investigation be understood in relation to this work, the statement is appended here.

"About a year ago[5] the writers undertook to determine the retina's sensitivity, relative and absolute, to colored light in terms of units that can be compared. Since several years will be required to complete this work, they have thought it best to publish a preliminary note showing briefly the purpose and scope of the investigation. The following points will serve to indicate what is being attempted in this study.

"(1) All measurements of sensitivity will be made in radiometric terms. This will give an expression of the sensitivity of the retina in units which are directly comparable with one another. At present we have no direct estimate of the comparative sensitivity of the retina to the different colors further than is ex-

[3] Coblentz, W. W. Instruments and Methods Used in Radiometry. Reprint No. 188, Bulletin of the Bureau of Standards, 1911, IX., pp. 22-23.

[4] Ferree, C. E. and Rand, G. A note on the Determination of the Retina's Sensitivity to Colored Light in Terms of Radiometric Units. Amer. Journ. of Psychol., 1912, XXIII, pp. 328-332.

[5] The first public statement of our intention to use radiometric units in the investigation of the retina's sensitivity to color was made to the committee in charge of the Sarah Berliner Research Fellowship, February 1. 1911.

pressed, for example, by the relative width of the collimator-slit that has to be used to arouse color sensation when a light-source of a given candle-power is used. This kind of comparison is obviously unfair because such different amounts of energy are represented from point to point in the spectrum that a given width of slit would admit many times the amount of energy at one part of the spectrum that it would at another. In short, no adequate estimation and expression of the retina's sensitivity to color, comparative or absolute, can be made by means of the methods now in common use.[6]

"(2) Comparisons of results on many other points with such disparate stimuli seem equally inadequate: the relative time required for the different color sensations to attain their

[6] Two criticisms have been received from private sources which it may be well to take account of here. In one the possibility of a point of view is implied, in the other a point of view is stated. The point of view, the possibilty of which is implied in the first criticism, is that it is not proper to estimate the sensitivity of the retina in terms of physical units, because it is generally conceded by modern investigators of color vision that the retinal processes which transform the physical energy of the color stimulus into nervous energy is essentially chemical in its nature; and one can not assume that a certain amount of physical energy arouses an equal amount of chemical energy in the retina, nor that equal amounts of physical energy arouse equal amounts of chemical energy. In answer to this, the writers would point out that these chemical substances are a part of the retina and their respective inertiae constitute one set of factors that determine the sensitivity of the retina to the different colored lights. It is not necessary to assume, therefore, that a given amount of physical energy arouses an equal amount of chemical energy, etc., in order to make our determinations of the comparative sensitivity of the retina to the different colors in terms of physical units. That would be necessary only if we were trying to separate out the nerve filaments, and to measure or compare their sensitivity to the different colors in terms of physical units. But even in chemical theories when speaking of the comparative sensitivity of the retina to the different colors, we do not mean the comparative sensitivity of the nerve filaments alone. We include the reaction of the chemical substances as well. Our contention, then, is that if the determination of the comparative sensitivity of the retina to the different colors is a proper problem, the determination should be made in terms of quantities that can be compared. This can be done either (*a*) by using lights equalized in energy and determining by means of a sectored disc the relative amounts of these lights that are required to arouse sensation; or (*b*) by using lights representing different amounts of energy and measuring directly in terms of radiometric units the amounts required to arouse sensation. We scarcely need point out that in speaking of the comparative sensitivity of the retina to the different colors we are not raising a new problem, but are merely recognizing a very old one.

The second criticism is in substance that a quantitative comparison of the effect of the different wave-lengths on the retina is improper because the different wave-lengths constitute stimuli too different in kind to permit such comparison. This criticism we leave open, because we do not wish to discuss in this paper the propriety of the problem of comparing sensitivities.

maximum of intensity, or retinal inertia; the relative rate of fatigue to the different colors; after-image and contrast sensitivity, etc.[7] In fact there is not a quantitative problem dealing

[7] It is conceivable that two points of view may be held with regard to what is meant by after-image and contrast sensitivity. (1) After-image and contrast sensitivity may express a relation between the amount of light required to arouse after-image and contrast sensations and the unit of light used. (2) It may express a relation between the amount of light required to arouse the after-image and contrast sensations and the amount required to arouse positive sensation. If the former view should be held it will be convenient to start with stimuli equalized in energy, and to determine the relative amounts of light required to arouse the after-image or contrast sensation by means of a sectored disc. If the second view should be held, the energy of the lights used may first be rendered proportional to the sensitivity of the eye to the colors in question; and the liminal values may then be determined by means of the sectored disc. In each case the relative sensitivity may be expressed by the inverse ratio of the open to the closed sectors.

Similarly two views may be held with regard to the determination of the comparative rates of fatigue, and of the development-time of sensation. (1) Lights equalized in energy may be used. (2) The energy of the lights may be made inversely proportional to the sensitivity of the eye to the different colors.

The need in both the above cases is equally great for a method of regulating and determining the amounts of light to be used in terms of a common unit of measurement. For example, in the second case two ways might be conceived of making the amounts of the colored lights proportional to the eye's sensitivity to these lights. (1) The limens might be determined and the intensity of the lights always be kept directly proportional to these liminal values. But the ratio needed to maintain this proportion could not be established unless some means were available of measuring the limen-values in terms of a common unit. And if this were established, we have no right to assume that it expresses the relative sensitivity of the eye to the colors in question when greater amounts of light are used. To make this assumption, we would have to maintain (a) not only that Weber's law holds for colored as well as for white light, but also that the ratio of increase which gives the just noticeable change in intensity is the same for all colors. We do not even know that there is a constant ratio over any considerable range of the intensity scale for even a single color. (b) We would have to maintain that this ratio is the same at the limen as at greater intensities, in other words, that Weber's law holds down to the limen. The consensus of opinion among investigators is that this is not true. (2) A curve may be constructed for the particular observer in which just noticeable changes in sensation are plotted along one coordinate and the energy changes required to give these changes in sensation are plotted along the other coordinate. The subjective equation, then, would be made by choosing points on the curves for each of the colors all representing the same number of just noticeable changes in intensity of sensation from the limen. The amounts of light required to give these equally intensive sensations could then readily be read off from the energy coordinate of the curve. The energy measurements required to construct such a curve would be comparatively simple, for once the limen-value was measured in terms of energy units, the remainder of the values could be determined by means of the sectored disc, that is, the energy change required to produce a just noticeable change in sensation is directly proportional to the ratio of change of open to closed sectors in the disc.

with the comparative functioning of the retina to the different colors in which there does not seem to be a need for the regulation and estimation of the stimulus in terms of a common unit of measurement. It is the purpose of the writers to extend the work as fast as possible into these related fields.

"(3) We wish to make a careful study of the sensitivity of the peripheral retina, quantitative[8] and qualitative, in a large number of meridians. In general too much uniformity has been assumed with regard to the sensitivity of the peripheral retina.

[8] The following are two of the points we wish to take up: (1) A determination will be made of the ratio of sensitivity of peripheral to central retina from point to point for a single color in several meridians. This will show at what rate the retina falls off in sensitivity in a single meridian, and how uniform this decrease is in the different meridians. We have found in a preliminary study that this knowledge is greatly needed in explaining certain phenomena of the peripheral retina. Futhermore, when this determination is made for each of the colors with which we wish to work, the ratios of sensitivity for these colors at all the points can be calculated and a definite answer can be given to the question whether or not uniformity of ratio obtains throughout the retina. This question has been given considerable importance in the discussion of color theories. (2) The limits of sensitivity will be investigated. In general two problems are involved here. (a) The limits may be considered in relation to the comparative sensitivity of the retina to the different colors. (b) They may be considered in relation to existing color theories. In the first of these problems the limits should be obtained with stimuli equalized in energy. So obtained the results will constitute merely another expression of the comparative sensitivity of the retina to the different colors. The second problem is more complicated and will later be made the subject of a separate paper. A word indicating its relation to our present plan of work may, however, not be out of place here. It may be logically assumed, for example, that the Hering theory demands that wherever the blue-sensing substance is found, the yellow-sensing substance must also be found. We have no means of knowing where these substances are except by the sensation aroused. Speaking in terms of the theory, then, we have a right to assume that wherever the blue sensation can be aroused the yellow sensation should be able to be aroused also, provided a sufficiently intensive stimulus be used. If, therefore, in passing towards the periphery of the retina, a point be found where blue can be aroused and yellow can not, the evidence will be strongly in favor of the conclusion that no yellow substance is present, unless it can be shown that elsewhere in the retina so much greater energy of yellow light than of blue is required to arouse sensation that the amount needed for this far peripheral point is greater than can be obtained. To establish this point the comparative sensitivity to these colors would have to be obtained at various points in the retina. This would involve the determination of a ratio based upon the amounts of blue and yellow light required to arouse sensation. Two methods of measurement may be used. (a) The amounts needed may be measured directly by means of a thermopile of the type we use, or other sensitive radiometer. In a determination of limens the number of readings required would render this method tedious. (b) The energy of the two lights may be made equal by means of a thermopile and the final amounts required to arouse sensation may be secured by means of a sectored disc. From the ratio of open to closed sectors the amount the light is cut down in each case may be calculated and the ratios of energy may be determined from these amounts.

Generalizations of great importance to color theory have frequently been based upon the results of work in which careful investigation was made in only one or two meridians. The conception of stable colors, and its application in support of the Hering *Urfarben* may be taken as a fair example of a sweeping conclusion which is based upon work too limited in its range. With a careful standardization of factors, an investigation in any considerable number of meridians shows that stable colors do not exist.[9] Many other points of interest have come out in our more detailed study of the peripheral retina. For example, we find in the periphery of the normal retina small areas which are exact replicas of the Schumann case of color-blindness.

"(4) We wish to conduct our investigation in full daylight instead of in the dark-room. This is to eliminate the influence of the field surrounding the colored stimulus and of the preexposure. When the surrounding field is black, white is induced by contrast across the stimulus color. Since the colors all differ in brightness, the induction takes place in different amounts for the different colors. This white, in proportion to its amount, reduces the action of the colors on the retina. Further, a given amount of white affects to different degrees the action of the different colors on the retina. To eliminate this twofold unequal action, the surrounding field should be made in each case of the brightness of the color to be used. This can be done by working in a light-room of constant intensity of illumination and making the surrounding field of a gray paper of the brightness of the stimulus color. In order to accomplish this, and at the same time be able to work upon any meridian of the retina we choose, we have constructed a special piece of apparatus which we call a rotary campimeter. The influence of preëxposure is even more important than of surrounding field. If the preëxposure is too black, white is added as after-image to the stimulus color. The effect of a black preëxposure upon the stimulus color is greater than the effect of a surrounding field of black, because more

[9] The following points are offered in support of the above statement. (1) A red and green cannot be obtained which in every meridian of the peripheral retina will pass into gray without an intermediate change into yellow or blue. (2) The amount of blue that has to be added to a mixture of red and green to produce gray varies from point to point in a given meridian even where the extramacular region alone is considered. Further, a series of determinations made for a given meridian will not hold for the remaining meridians. (3) A red, green, and yellow can not be obtained which will not change in color-tone in passing from the center to the periphery of the retina in a single meridian.

Blue alone of the four principal colors is stable in tone for all parts of the retina.

white is added as after-image of preëxposure than is induced by contrast from the surrounding field. This effect also can be eliminated only by working in a light-room of constant intensity of illumination and by choosing as preëxposure a gray of the brightness of the color to be used."

B. Description of Optics-Room and Apparatus.

The work was carried on in a well-lighted optics-room, 12½ x 10 ft. The room is situated on the upper floor of an isolated building and is lighted by a skylight, 8 x 7½ ft. Beneath the skylight, two diffusion-sashes, 4 x 7½ ft. are swung on hinges so that they can be raised or lowered as desired. The framework of these sashes is made of a light-weight iron. For convenience of local control of illumination, if needed, each sash is divided into four units by means of cross-pieces. The sashes are filled with double-strength glass ground on one side, so adjusted to the frame that they can be removed easily for cleaning or for the substitution of some other kind of glass in case that is desired. This glass diffuses the light so effectively that local shadows cast by the cross-pieces in the framework of the skylight are completely eliminated, while the sudden changes of illumination produced by the passage of the sun behind a cloud are reduced to a minimum. This diffusion seems to have the further advantage of reducing the yellowness of direct sunlight below the limen of sensation. At least, when working under the sash, the observer never judged a gray exposed through the campimeter-opening as yellow under any local conditions, as frequently happened when working under direct sunlight.

The room is planned also so that small changes of illumination can be produced, ranging from the intensive illumination of a south-exposure skylight to the blackness of a moderately good dark-room. Two provisions are made for this. (*a*) The diffusion-sashes are made so that any or all of the panes of ground glass can be quickly and easily taken from the sash, and anything can be substituted that is desired; or the illumination can be varied by placing layers of tissue-paper above the glass. (*b*) The room is provided with two curtains mounted on heavy spring rollers. One is a white curtain made of thin muslin; the

other is a black light-proof curtain so mounted that, when drawn, its edges are deeply enclosed in light-proof boxing extending along the four walls of the room. One or both of these curtains can be drawn any distance that is desired, and the illumination can thus be changed gradually from a very intense brightness to a fairly good blackness. To aid in getting dark-room effects, the doors of the room are carefully boxed and curtained. One requirement of a perfect dark-room, however, is lacking, namely, the walls and floor of the room are painted white. This is because it is of advantage in the light-room work, and because complete blackness is not needed in the type of work for which the room is devised.

The apparatus used in the investigation consists of a rotary campimeter devised to meet the requirements of the task in hand by Dr. C. E. Ferree[10] of Bryn Mawr College. The object of this apparatus is to add to the vertical campimeter the rotary features of the perimeter and thus to allow investigation of every possible meridian of the retina with as much ease and precision as was possible with the old form of campimeter in the nasal meridian only, or at most, in the nasal and temporal meridians. The apparatus consists of two parts with proper supports and accessories; a stimulus screen, and a campimeter screen which rotates on a collar around a circular support. The stimulus is exposed through an opening in the center of the campimeter screen. One arm of the framework of this screen carries the fixation-points, and also a right-angled extension which allows fixation to be given at an excentricity of 92°. This arm may be rotated to any position desired, and thus any meridian of the retina may be explored. In order that the sensation received in the peripheral retina may be accurately expressed in terms of color- and brightness-values of the central retina, the fixation-arm of the screen is further provided with a small detachable motor upon which may be rotated the proper combination of discs for matching peripheral sensation. This increases greatly the definiteness of work on the sensitivity of the peripheral retina.

[10] For the orginal description of this apparatus, see C. E. Ferree. Description of a Rotary Campimeter. Amer. Journ. of Psychol., 1912, XXIII, pp. 449-453.

The feature was added to the apparatus so that complete maps might be made of the changes in the sensitivity of the retina from center to periphery and from one meridian to another, with tables showing the value of the changes from point to point.

Photographs of the skeleton apparatus and of the front and back views of the campimeter in readiness for use are appended.

Figure 1 shows the skeleton apparatus. It consists of the following parts: supporting base, frame for campimeter screen, and frame for the stimulus card. The supporting base consists of a horizontal steel bar, 83 cm. long, supported by two iron tripod rests (B and B′). To this bar are clamped two uprights (C and C′), which are adjustable along its length. The anterior upright (C) supports the frame on which the background of cardboard and the campimeter screen (D) are fastened. The posterior upright (C′) supports the stimulus frame (E). The height from the table of each of these frameworks is adjustable by means of set-screws (F and F′). The framework for the campimeter screen consists of central support and radiating arms. The central support consists of a stationary brass ring,[11] about which rotates a larger brass collar (H), 20 cm. in diameter. The back surface of collar (H) is graduated from 0° to 360°. To this collar are fastened the radiating arms. There are eight of these arms, one for each 45° mark of the graduated collar. They are made of steel and are 2 cm. broad and 40 cm. long. The eighth arm (I-I′) differs from the other seven. It forms a right angle, one side of which is in the plane of the background and the other in front of this plane. The part in the plane of the background is 30 cm. long, and the part at right angles to this

[11] This ring was made large in diameter for two reasons. (*a*) The ring had to be made very thick in order to give sufficient rigidity to support the campimeter screen and to furnish proper attachment for the rotary collar. Had the circumferance been small, the effect of the ring would have been that of a short tube. If the stimulus were viewed through a short tube, an induction factor would have been involved which would have been difficult, if not impossible, to standardize. The opening in the ring was, therefore, made considerably larger than any stimulus we wished to use in order to avoid the introduction of this factor. (*b*) The large circumference of the ring makes the apparatus available for investigating the effect upon sensitivity of varying the size of stimulus.

plane is 28 cm. long. The arm is graduated from 18° to 57° along the section that lies in the plane of the background and from 57° to 92° along the section at right angles. The graduations are based on the arc of a circle of 25 cm. radius. The arm is also split lengthwise to form two narrow arms, each 1 cm. wide, so separated that there is an opening (J) 0.8 cm. in width between them to admit the shank of the motor for rotating the discs needed to match the peripheral sensation. The opening to admit the shank of the motor may be clearly seen in all the pictures of the campimeter. The motor is shown at K on the right of Figure 1 and more clearly on the left of Figure 3. It has a shank 4 cm. long and 0.3 cm. in diameter, which can readily be thrust through the opening (J). The weight of the motor is so great that it can not be clamped to the arm (I-I′) and thus be shifted with the arm as the retina is tested in different meridians. It has then to be supported so that it can readily and quickly be moved to any point in any meridian to which the arm (I-I′) may be rotated. This is accomplished by the use of two rods—one vertical (L) and the other horizontal (M). The vertical rod (L) may be clamped to the table or other support on either side of the campimeter, and M is clamped to L. The vertical adjustment for any setting of the motor can thus be made along L and the horizontal adjustment along M. Holes are punched in each of the eight arms at six or more places to allow the insertion of small metal fasteners to hold the background screen to the frame. The stimulus frame may be seen at E. It is 20 cm. square and carries a groove for the insertion of the stimulus card. The stimulus card may be made of whatever colored paper the experimenter desires to use.

Figure 2 shows the front view of the campimeter in readiness for use; and Figure 3, the back view. A cardboard background has been fastened to the steel arms by means of paper-fasteners. Since the background is fastened to the arms attached to the brass collar (H), a circular gap is left at its center. This gap is filled by a disc (N), shown in Figure 3, which has been fastened to the arms just outside of the collar (H). The disc is 27 cm. in diameter and contains the stimulus-opening (O), the size

of which may be varied to accord with the purpose of the investigation. In the experiments reported in this paper, it was 15 mm. in diameter throughout. In order to complete the graduations on the fixation-arm to the stimulus-opening, disc (N) is graduated from 0° to 18°. A background 40 cm. in height is fastened to the extension arm (I). In the picture a paper screen made of No. 7 of the Hering series of grays has been attached by thumb tacks to the cardboard background. A strip of paper of the same quality as the background is placed along the opening (J), and the graduations from 0° to 92° are pricked on this strip as indicated by the markings on the back of disc (N) and arm (I-I′). These constitute the fixation-points. The card in the stimulus frame (E) is seen through opening (O). A disc (P) composed of black and white sectors has been placed on the motor (K).

The method of using the apparatus is as follows: The observer is seated in front of the campimeter screen with his head held in a rigid position by means of a mouthboard bearing the impression of the teeth in sealing wax. Since the graduations of the fixation-arm are based on the arc of a circle of 25 cm. radius, the distance of the eye from the stimulus-opening is chosen as 25 cm. The position of the eye in the observing plane may be obtained according to the method described by Fernald.[12] In order to facilitate excentric fixation in the nasal and temporal meridians, the head should be turned 45° nasalwards or temporalwards, as the case may be. With the head so placed, the eye can swing easily from the stimulus-opening to a fixation-point whose excentricity exceeds 90°. The unused eye is closed and covered by a bandage. The arm (I-I′) is placed in the meridian desired, the position being indicated by the graduations on the collar (H). The experimenter covers the stimulus in the stimulus frame with a card, which we shall call the preëxposure card, while the observer takes the fixation required. At a signal given by the observer, the preëxposure card is withdrawn, the stimulus is exposed for three seconds, and the preëxposure card is replaced

[12] Fernald, G. M. The Effect of Achromatic Conditions on the Color Phenomena of Peripheral Vision. Psychol. Rev., Monograph Supplements, 1909, X., p. 18.

over the stimulus. The observer is required to rest the eye after each observation. Further provisions against fatigue are made by periods of rest after each fifteen minutes of observation.

When it is desired to measure the stimulus as seen in the peripheral retina in terms of brightness- and color-values of the central retina, the motor shown at K in Figures 1 and 3 is used. The method of making the measurement is as follows: If a direct vision judgment, for example, of the appearance of yellow at 25° in the temporal meridian is wanted, the cord (R) carrying a movable fixation-point, seen in Figure 2, is fastened in front of the 25° point on the graduated background. The observer, in position, fixates the 25° point and brings the movable point in line with the eye and the 25° point. This point then serves as the new fixation-point, and the graduated strip covering the opening (J) is removed. The required discs are placed on the motor immediately behind the new fixation-point, and their proportions are changed until the observer judges that the sensation aroused in the periphery is matched by that aroused in the center by the measuring-disc on the motor. In making this judgment, the method of ascending and descending series was used.

In this investigation, stimuli of blue, yellow, red, and green pigment papers of the Hering series were employed. White, black, and gray papers of the Hering series served to make the backgrounds. Results were obtained from three observers: Miss Campbell, *C*, graduate student in Bryn Mawr College, who had no knowledge of the problem in hand, Dr. Ferre, *B*, and the writer, *A*.

C. Determination of the Brightness of the Colored Stimuli Employed in the Investigation.

At every turn in our problem, it was necessary to know the black-white-values of the colored papers that formed our stimuli, as they appeared in the central and peripheral retina at full and decreased illumination. It was thought best, therefore, to devote a separate chapter of our report to a discussion of the methods used in determining these values. The method of flicker photometry was used throughout except at the limit of peripheral color vision, where it was possible to use the method of direct com-

parison. The black-white-values of the colors were determined for the central retina by means of the Schenck *Flimmer Photometer.* As this apparatus is not adapted to indirect vision work, it was necessary to devise a means by which the brightness of the stimuli at any point in the peripheral retina could be determined by the flicker method. The conditions of our experiment made it essential that these determinations be made not only in terms of black-white-value but also of colorless pigment paper, the brightness of which would approximately be the same as that of the colored stimulus. In order to make the latter determination possible, a series of gray papers varying in brightness by very small amounts was required. The Hering papers, ranging in number from 1 to 50, were found to furnish a series which varied in brightness by amounts sufficiently small to serve our purpose.

The use of the flicker method in photometry is based on the fact that two surfaces are considered equal in brightness when upon their alternation one with the other at a certain favorable rate of speed, no experience of flicker results. Obviously a very important point in the method is to determine what this rate of alternation should be. It should be determined empirically for each observer in a preliminary experiment. To make the determination we must be able to produce known brightness differences in different parts of the scale and to try the effect on flicker of different rates of speed for these brightness differences. This can be accomplished by making the preliminary experiment with colorless surfaces, for very small differences in brightness between two colorless surfaces can be estimated by the method of direct comparison. (This could not be done if one or both of the surfaces were colored.) Working then with colorless surfaces by the aid of the method of direct comparison, not only do we know at every stage of the experiment how much brightness difference is produced, but we standardize the flicker determination in terms of the method of direct comparison to which all indirect methods of determining brightness equality must conform if their results are to be of any value. In making our preliminary determination, then, colorless surfaces should be used and that rate of alternation, equal to or in excess of the

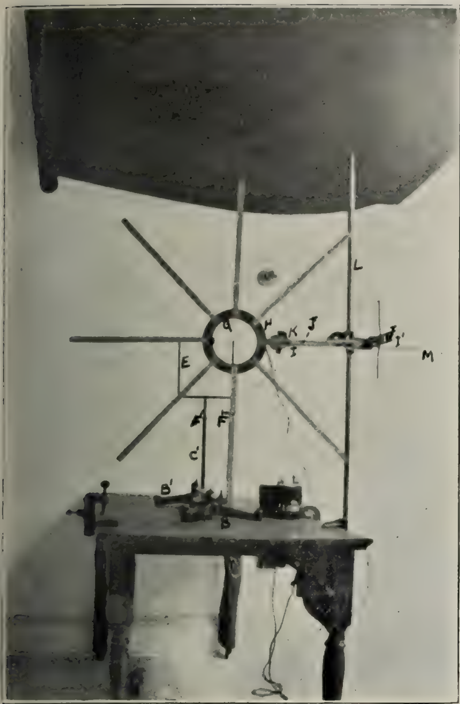

Figure I

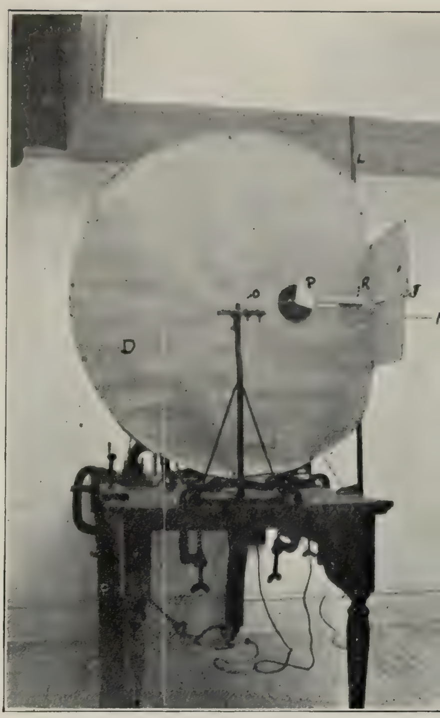

Figure II

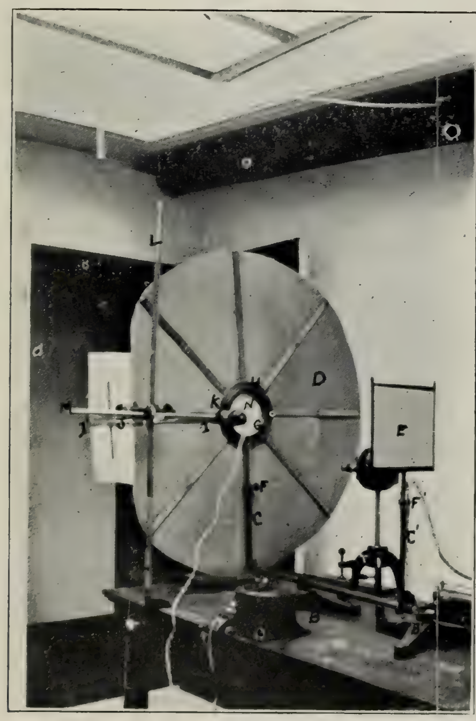

Figure III

fusion rate for the color in question, should be selected at which the smallest difference in brightness between the two surfaces produces flicker. This speed may be considered as giving the maximum sensitivity to the method for the given observer and may be used for that observer in the color work. Applying this method to the determination of the brightness of a colored paper, we may consider that a colored and a gray paper are of equal brightness when no flicker is produced by the rotation of equal sectors of each at the chosen rate of speed. In order to prevent induction from the surrounding field, the rotating disc should be viewed through an opening in a screen of the same brightness-value as the disc itself. This requires that the gray sector, the colored sector, and the screen all be of equal brightness-value. The final value of this brightness must, however, be reached by a series of approximations. That is, the gray sector and the screen must at each trial be chosen of the same brightness, and both must be changed alike until a gray is finally obtained which does not produce flicker when it is rotated with the colored sector at the chosen rate of speed. Owing to the great number of steps in the series of approximations needed to reach the gray-value of the color, it was impracticable to change the large campimeter screen at each step. Moreover, to prevent brightness induction over the stimulus, it was not necessary to have so large a part of the surrounding field, as was comprised in the entire screen, of the same brightness as the stimulus. Squares 30 cm. on a side were found to be quite adequate for the purpose and to have the practical advantage that they could be quickly and easily changed. Since the sensitivity of the retina to flicker varies from point to point as we pass from the fovea outwards, it is found to be important that the opening in the screen be made small so that the area of the retina stimulated shall be uniformly sensitive to flicker. And, further, since the area of the retina influenced by a given stimulus decreases as we pass from the fovea to the periphery, because of decrease in the visual angle, it is necessary that the stimulus-opening be proportionately increased in the peripheral observations, in order to maintain the size of the stimulated area of the retina constant. Both of these conditions were met sufficiently accurately for our purpose, by using two

openings of different size, the smaller to be employed at all points from the fovea to 20° peripheralwards, and the larger to be used from the 20° point to the extreme periphery.

The method used to determine the brightness in terms of gray paper of a given color in central vision was as follows. From the series of squares of gray papers having the smaller of the two sizes of stimulus-openings (3 mm. x 1 mm.) one was selected which was judged by the method of direct comparison roughly to approximate the brightness of the color in question. This square was fastened upon the campimeter screen so that the stimulus-opening passed vertically through the center of the opening in the original screen. A disc compounded of 180° of the given color and 180° of the gray of the brightness of the square, was rotated behind the stimulus-opening and the observation made for flicker. Lighter and darker grays were in turn substituted in disc and screen and the observation was repeated. The gray which produced no flicker at the chosen rate of speed is, in terms of the method, the gray of the brightness of the color. The determinations were not at all difficult nor uncertain. Flicker was readily discernible in the gray lighter and darker than the one which was chosen, at the speed of rotation at which the one chosen showed no flicker. Our determinations showed that at the standard illumination[13] used throughout the work, the method of obtaining which will be discussed later, the brightness of Hering blue for central vision equalled that of Hering gray No. 41; of red equalled gray No. 24; of green equalled gray No. 8; and of yellow equalled gray No. 2. These values were the same for all of our observers.

For the determination of the brightness of the colored stimuli in peripheral vision, the same method was used with the exception that at points in the periphery beyond 20°, the screens having the large stimulus-openings, 15 mm. in diameter, were used. The results of the peripheral experiments differed from the central at standard illumination only in case of blue. Blue was found to lighten in the periphery so much that gray No. 21 was determined

[13] Measured in foot-candles by means of the Sharpe-Millar portable photometer, the standard illumination equalled 390 foot-candles.

by one observer to equal it in brightness. The determinations at the peripheral limit of sensitivity to color were made by the method of direct comparison. On the campimeter was mounted a gray screen for each of the colors in turn the brightness of which was such that when the stimulus was observed beyond the limits of color sensitivity, the color in each case changed into the gray of the brightness of the screen. If a gray lighter or darker was used, the stimulus appeared either darker or lighter than the screen.

The black-white-values of the colors for peripheral vision can not be determined directly because for the direct determination the Schenck *Flimmer Photometer* with its graduated sectors of black and white or some similar device must be used. This photometer is not adapted for peripheral vision work. A determination, then, had to be made with the photometer in the central retina for the grays which had been found by the method described in the preceding paragraph to equal the colors in brightness in the peripheral retina.

In one section of the investigation, it was found necessary to work at decreased illumination, and to know the brightness of the colored stimuli under these conditions. The decreased illumination was obtained by drawing the black curtains, until the illumination was slightly less than that of a cloudy afternoon.[14] The colors appeared a little less saturated, and slightly altered in color tone. The green was a trifle bluish, the yellow was changed toward orange, and the blue appeared slightly reddish. Determinations were made at this illumination according to the method described above, of the brightness of the colors in central and in peripheral retina. The results are stated in Tables I and II. The first column shows the white-black-values of the stimuli at standard illumination in central vision; the second shows the same values in terms of the Hering gray papers; the third represents the brightness-values in peripheral vision at the limit of sensitivity; and the fourth and fifth columns show the brightness of each stimulus at the center and at the periphery under conditions of decreased illumination.

[14] Measured in foot-candles by means of the Sharpe-Millar portable photometer, this decreased illumination equalled 1.65 foot-candles.

Table I records the results of Observer *A*; Table II those of Observer *C*.

TABLE I.

A. Showing the brightness-values of the Hering principal colors at standard and decreased illumination.

Stimulus	Brightness at Standard Illumination			Brightness at Decreased Illumination	
	At center		At limit of sensitivity in periphery	At center	At limit of sensitivity in periphery
Yellow	white 236° black 124°	gray no. 2	gray no. 2	gray no. 2	gray no. 3
Green	white 100° black 260°	gray no. 8	gray no. 8	gray no. 8	gray no. 5
Red	white 41° black 319°	gray no. 24	gray no. 24	gray no. 24	gray no. 50
Blue	white 15° black 345°	gray no. 41	gray no. 28	gray no. 35	gray no. 13

TABLE II.

Observer C.

Yellow	white 236° black 124°	gray no. 2.	gray no. 2	gray no. 2	gray no. 3
Green	white 100° black 260°	gray no. 8	gray no. 7	gray no. 7	gray no. 4
Red	white 41° black 319°	gray no. 24	gray no. 24	gray no. 24	gray no. 50
Blue	white 15° black 345°	gray no. 41	gray no. 21	gray no. 35	gray no. 7

Whether or not the peripheral retina functions differently from the central retina and must, therefore, be assumed to possess a different sensory mechanism, is a question of considerable importance to theories of color vision. Upon this question the results shown in Tables I and II have a direct systematic bearing. But since the comparative functioning of central and peripheral retina will be made the subject of a later report of work already completed by the writer, the significance of these results need not detain us here. We need only note in passing,

that the brightness changes that occur when a stimulus is carried from central to peripheral vision are similar to those that obtain in central vision when the illumination is decreased. With regard to this point our tables show (*a*) that in the peripheral retina at standard illumination, the colors have very nearly the same brightness relations that they have in the center at the decreased illumination we used; and (*b*) that the brightness relations of the colors seen in the peripheral retina at decreased illumination approximate those of the colors in the center when the illumination is further decreased. These latter changes known as the Purkinje phenomenon are in the following directions: blue and green relatively lighten; red and yellow relatively darken.

In Tables I and II, showing the comparative brightnesses of the color sensations at center and periphery, the lightening of blue and green and the darkening of red in the periphery are sufficiently pronounced to need no comment. But measured by these results, the change in yellow seems to be insignificant. If, however, yellow is observed in the periphery at decreased illumination and is compared with gray No. 2, that is, the brightness of yellow both in center and periphery at standard illumination and in center at decreased, it appears to be much darker than the gray screen. Contrast from the screen exaggerates this darkening to some extent but the change in the brightness of the sensation due to peripheral stimulation alone is considerable.

D. The Factors Investigated.

The factors we have investigated with regard to their influence upon the color observation are: (1) the brightness of the stimulus; (2) the brightness of the field surrounding the stimulus; (3) the brightness of the preëxposure; and (4) the general illumination of the retina.

1. *Brightness of the Stimulus.*

It will be remembered from the historical discussion (p. 45 ff.) that the four men,—Bull, Hegg, Hess, and Baird,—who recognized the need of equating the intensity of colored stimuli for a determination of the relative limits of color sensitivity, equated them also in brightness. They apparently assumed the need of

this equation without having investigated the influence of the brightness difference between the colors upon the breadth of the color zones. As a result of a careful investigation of this question, we are able to show that not only is no advantage gained by equating the brightness of colors when determining their limits of sensitivity, but a positive disadvantage is suffered. The following reasons may be cited in support of the latter statement. (*a*) The quality of certain colors is changed when their brightness is altered. This disadvantage, first mentioned by Chodin, was a source of great difficulty to Hegg, as we have seen (p. 74).[15] (*b*) Colored stimuli which have been equated in brightness are necessarily reduced in intensity. For this reason, no true nor comprehensive estimate of the color sensitivity of the retina can be obtained with stimuli equated in brightness. (*c*) The technique involved is extremely cumbersome.

Our investigation of the influence which the brightness difference between the four principal colors exerts upon their limits covers four points. (*a*) The work on the first took its start from Hegg.[16] Hegg apparently assumed that the difference in the brightness of the four colors,—red, green, blue, and yellow,—at full saturation is sufficient to affect their limits, and, therefore, that they must be equated in brightness before a determination of their relative limits is made possible. With the view of testing the validity of this assumption, we sought to ascertain whether a brightness change in any one of the four colors, equal to the maximal brightness alteration made in Hegg's equation, affects the limits of sensitivity to that color, provided the alteration is produced without changing the amount of colored light coming to the eye. The test was made doubly strict by varying the colors both toward white and toward black, thus covering a variation whose range was twice as great as was required. That is, both white and black in turn were added to each of the colors in

[15] Mrs. Franklin remarks concerning Hegg's oil papers: "Of the 'normal' colors prepared by Hegg, the red and the yellow would not strike the plain man as at all deserving of the name" (Psychol. Rev., 1897, IV., p. 96).

[16] A start was taken from Hegg, in preference to the other three investigators, because he is the only one who gives adequate numerical data concerning the extent of brightness alteration he made in obtaining this equation.

amounts equal to Hegg's maximal change, and the limits of the stimuli thus obtained were compared with each other, and with the limit of a stimulus equal to them in physical intensity and to the original color in brightness. No effect whatever on the limits was found as a result of these brightness alterations. (*b*) We next sought to ascertain whether a brightness equation is necessary when working with the standard pigment papers of the Hering series. A determination of the maximal brightness difference between the colors was made at the limit of sensitivity to each, and the above experiments were repeated using the maximal value obtained in these determinations, as the amount of variation. In no case were the limits affected. (c) Following Hegg's plan of equating the four colors to one of mid-brightness, we next determined the maximal amount of change required to equate the standard Hering colors to the brightness of green. Since the amount of change was obviously much less than the variations used in (*b*), it was not necessary to repeat the experiments on the limits of sensitivity with this amount of variation. In two ways, then, we shall have shown that it is unnecessary to equate the Hering colors for brightness when determining their relative limits of sensitivity, since neither the maximal amount of change required to bring them all to a medium brightness, nor the maximal amount of brightness difference between the colors, has any effect upon the color limit when this change is applied as a variant in the direction of either white or black, provided that the amount of colored light coming to the eye remains unaltered throughout. These results may seem contradictory to the statement made by certain other writers and by ourselves[17] that dark colors appear more saturated than light colors of equal physical intensity, that is, white exerts a greater inhibitive action than black upon color. This brings us to our fourth point. (*d*) We have to explain why these brightness changes which are known in general to affect the sensitivity of

[17] Ferree, C. E. and Rand, G. Colored After-image and Contrast Sensations from Stimuli in Which No Color Is Sensed. Psychol. Rev., 1912, XIX., pp. 215; An Experimental Study of the Fusion of Colored and Colorless Light Sensation: The Locus of the Action. Journ. of Philos. Psychol. and Scientific Methods, 1911, VIII., pp. 294-297.

the retina to color do not change the limits of color. The explanation, as will be shown on p. 104, is found in the extreme rapidity with which color sensitivity of the retina falls off near the limits. The amounts of brightness dealt with in the above cases do not produce a sufficient change in the saturations of the light and the dark color to cause their limits to differ by even 1°, because the stimuli reduced in intensity by this amount of brightness are still sufficiently intensive to cause the color limits to occur within the zone of rapid decrease in sensitivity. If the stimuli had given a very small amount of colored light to the eye, and the limit of sensitivity had consequently occurred nearer the center of the retina where the sensitivity falls off more gradually, the difference in saturation between a dark and a light color of equal physical intensity, might have been sufficient to cause the latter to have a narrower extent of visibility. But since the amount of intensity at which this exception occurs is much less than is ever likely to be used in investigating the color limits, the exception can scarcely be entitled to more than theoretical consideration. The writer regrets to report that she has not carried on this investigation with spectral light. While she has no reason for believing that the results would in general be different, still for the sake of knowing the exact values of the brightness quantities obtaining in case of spectral colors, she hopes to make the investigation in the near future.

To investigate these points, it was necessary to devise a method whereby the brightness of the color can be altered without changing the amount of colored light coming to the eye. When one is working with pigment papers, the brightness of the stimuli can easily be varied without changing the intensity of the stimulus. For example, discs can be compounded of 260° of yellow and 100° of white, 260° of yellow and 100° of black, 260° of yellow and 100° of the gray of the brightness of yellow. In these cases we have, in order, a tint of yellow, a shade of yellow, and a yellow reduced in saturation but not changed in brightness, —all giving the same amount of yellow light to the eye. If it should be desired to make the tints darker and the shades lighter, the brightness sectors can be chosen of white or black in any proportion that is required.

In determining the size of the brightness sector to be used for the first point in this investigation, we are obliged to proceed largely by inference from Hegg's rather meager report of his work. He had equated the peripheral brightness-values of his four stimuli to green. In doing this, 84° of white and 5° of black were added to red. No statement whatever is made by him with regard to the amount of white and black added to blue and yellow. These amounts have, therefore, to be inferred. In doing so, care was taken to make the amount sufficiently large to give our test due rigor. We have mentioned that blue lightens in the periphery until its brightness is much like that of red. For Observer *A* it is slightly darker than red, for *C* slightly lighter. It is fair, then, to assume that 100° represents the maximal brightness difference that Hegg found to obtain between the colors in their peripheral values. Observations were taken from sets of discs composed of sectors of 260° of each of the four principal colors and 100° in turn of white, of black, and of the gray of the brightness of the color. The surrounding field and preëxposure in each case were of the gray into which the stimulus color changed at the limit of sensitivity. Several observers were used and several meridians explored, but in no case could a difference in the limits of sensitivity be detected for the color mixed with white for the color mixed with black, and for the color mixed with the gray of the brightness of the color. Space will not be taken here to record the results for all observers in all meridians investigated. The results obtained for Observer *A* for the temporal and nasal meridians are selected as typical. They are shown in Table III.

We have seen that the alteration made by Hegg in his brightness equations, when applied to stimuli of Hering standard papers, does not affect their limits of sensitivity. We now pass to our second point, namely, whether the full brightness difference in these colored papers should be considered as in any way affecting their limits. This is somewhat different from the preceding point in which we were concerned merely to find out whether Hegg's attempt to reduce all the colors to a mid-brightness could be considered as having any effect upon their limits.

TABLE III.

A. *Showing the limits of sensitivity*[18] *when the colors are mixed in turn with* 100° *of gray of the brightness of color,* 100° *of white, and* 100° *of black without altering the amount of colored light coming to the eye.*

Stimulus	Meridian	Limit of stimulus when mixed with 100° gray	Limit of stimulus when mixed with 100° white	Limit of stimulus when mixed with 100° black
Yellow	Temporal	42°	42°	42°
Green		35°	35°	35°
Red		41°	41°	41°
Blue		51°	51°	51°
Yellow	Nasal	88°	88°	88°
Green		59°	59°	59°
Red		85°	85°	85°
Blue		91°	91°	91°

We wish here to find out whether the actual difference in brightness between the extreme members of the series, blue and yellow, affects the limits of any one of the series. To do this, our method was to determine the difference between blue and yellow at their limits of sensitivity, to vary each color toward both white and black by the amount of this difference, and to find out whether the limits of the light and the dark stimulus differ from each other or from that of a stimulus of equal intensity which has retained the original brightness of the color. This amount of variation was greater than was needed in case of red and green, because they do not differ from any member of the series by so great an amount. We have used this maximal amount, however, because we have not wished to leave room for any question as to the rigor of our test.

In order to ascertain the difference between the white-values of the colors seen in the extreme periphery, the Hering gray that represented the peripheral brightness of each stimulus as determined by the method of direct comparison at the limit of sensitivity (see Tables I and II), was mounted on the Schenck

[18] The point at which color loses all trace of its original quality is recorded as the limit of sensitivity.

Flimmer Photometer, and its white-value determined. For Observer *A,* blue was the darkest color. Its brightness was equal to white 37°, black 323°; that of red was equal to white 41°, black 319°; that of green was equal to white 100°, black 260°; that of yellow, the lightest color, was equal to white 236°, black 124°. The maximal brightness difference, then, was between blue and yellow, and was equal to 199°. To ascertain whether this brightness difference is sufficiently great to influence the breadth of the color zones, the limits of stimuli composed of 161° of each color and 199° of black, and of 161° of color and 199° of white were compared with each other and with the limit of a stimulus composed of 161° of color and 199° of gray of the brightness of the color. The first two stimuli, it will be observed, were composed of the color altered in brightness toward black and toward white by an amount equal to the difference in white-value between blue and yellow; the third stimulus retained the original brightness of the color while it sent the same amount of colored light to the eye as the other two. In every case, on either the nasal or the temporal meridian, the limit of color visibility was the same whether the stimulus was the color in its original brightness or whether its brightness was changed in either direction, toward black or toward white, by an amount equal to the maximal difference between the white-values of the colors as seen in peripheral vision.

As we have said, our test is unnecessarily severe. Not only have we lightened blue and darkened yellow by an amount equal to the difference in their white-values, but we have also darkened blue and lightened yellow by the same amount. If a brightness equation were found to be necessary, the variation would by no means be as wide as the one we have made. It would be necessary merely to darken some colors and to lighten others to a medium brightness.[19] We feel confident then in stating the following

[19] The change we have made in one direction is no greater than had to be made by Baird who equated all of his colors to the brightness of blue. Baird, it will be remembered, was forced to employ this brightness as standard because his equation of brightness was made by interposing an episcotister between the stimulus and the eye of the observer. This method permitted change only in one direction, towards black. The defects of his method

two points:—(*a*) The amount of change required to equate in brightness the colors, red, green, blue, and yellow, has no effect upon their color limits and the precaution of equating is, therefore, superfluous. (*b*) The actual brightness difference in the colors at standard saturation has no effect upon their relative limits.

While we have shown that variations of brightness in the above amounts do not affect the limits when there is no alteration in intensity of the colored light, we do not claim that there might not be a change sufficiently large to influence the limits. This would be a broader thesis than we wish to maintain. We have merely been concerned with showing that brightness alterations as great as the difference between the white-values of the Hering standard papers do not affect the limits. Strictly speaking, this is as far as our criticism of previous attempts to standardize brightness need carry us. But it is a matter of fact that a color mixed with black gives us a sensation that is more intensive than that produced by a color of equal physical intensity which is mixed with white, and that the limen of color is much lower when the color is mixed with black than when mixed with white. Brightness change, then, does affect the retina's sensitivity to color, and, within limits, the breadth of the zones of sensitivity. We have, therefore, extended our investigation to explain why changes of the order given above do not affect the color limits, and to determine roughly to what extent brightness change may be made without affecting them. As already indicated we must look for the explanation of our results to the rapidity with which the sensitivity of the retina falls off from point to point from center to periphery. If, for example, it be found that sensitivity falls off gradually from the fovea to near the limits (as determined with stimuli of full intensity,) and from that point on, it falls off abruptly, we might expect that light and dark colors of equal physical intensity will have different limits up to the point on the retina at which the abrupt

have already been pointed out. With a spectroscopic mixer as the ideal apparatus for investigations with the light of the spectrum, the brightness changes can be readily made in both directions, as they can with pigment paper stimuli.

change in sensitivity begins, and the same limits from that point on. It is obvious that in either case, whether or not there is a difference in limit, depends upon whether the difference in the inhibitive action of white and black upon the color is equal to the amount of change of intensity required to affect the limit. If sensitivity falls off gradually, a relatively small change in intensity is sufficient to widen the limit, and, if abruptly, a relatively large amount of change is required.

By way of explanation, it is our purpose to show (*a*) that the sensitivity of the retina falls off gradually to a point within 5° of the limit and from that point to the limit, it falls off very abruptly; (*b*) that the white and black sectors added to the colored stimuli in the foregoing tests did not weaken the stimuli sufficiently to narrow their limits more than 3°; and (*c*) that within the zone 3° from the limit, the difference between the apparent saturations of our light and dark stimuli was not sufficient to affect their limits.

An inspection of the results given in Table VIII and discussed in the next section (p. 117 ff.) will show the rate at which the sensitivity of the retina falls off from the fovea to the periphery and will establish our first point. The decrease is gradual from the center to within 5° of the limit, beyond which point it grows progressively more abrupt, becoming extremely abrupt from a point 3° from the limit to the limit. For example, when the screen and preëxposure of the gray of the brightness of color are used, the limen of yellow at the fovea is 18°; at 39° from the fovea in the temporal meridian, that is, 5° from the limit of yellow, it is 100°. Thus over a space of 39°, the limen has increased only 82°, and average of little more than 2° of increase per degree of retina traversed. At 41°, however, it has reached a value of 150°, an average of 34° of increase per degree of retina traversed; at 42°, a value of 240°, an average of 90° of increase per degree of retina traversed; at 43°, a value of 330°, an average also of 90° per degree of retina traversed. With regard to the second point, it will be remembered that the extreme amount of white or black we added to our colors was 199°. This left 161° of color in the stimulus discs. Table VIII

(page 119) which gives the values of the color limens at different points near the limit, shows that this amount of color is above the limen for each color at 3° from the limit. In our tests, then, we were working well within the 5° limit bounding the zone of abrupt decrease in sensitivity, as our explanation required us to show. With regard to the third point, it will be seen from the same table that, when working at the point 3° within the limit, in order to extend the limit 1°, an increase of the colored sector by amounts ranging from 65° in the case of blue to 115° in the case of green, is required. It scarcely need be pointed out that the apparent saturation of a stimulus composed of 161° of color and 199° of black is not greater than the apparent saturation of a stimulus composed of 161° of color and 199° of white by an amount equivalent to from 65° to 115° of color.

Having explained why brightness differences equal to those found in red, green, blue, and yellow papers of standard saturation have no effect upon the limits of color sensitivity, we turn next to a determination of the range within which brightness change may be made without affecting the limits of sensitivity. Two ways occur to us by means of which a rough estimate of this range may be obtained. (a) Stimulus colors at full saturation may be used and the brightness excitation be added as after-image or contrast or both. In this way the amount of colored light coming to the eye is not altered by the brightness added, that is, the physical intensity of the color in the stimulus is not affected. If we wish to use the contrast and after-image effects, the card which covers the stimulus before exposure can be adjusted so that an intensive after-image is superimposed upon the stimulus when the card is removed. By a proper regulation of this card and of the campimeter screen, which causes contrast induction across the stimulus, varying amounts of white and black can be added to the stimulus, care being taken to measure these amounts and to keep them equal, each to each. Since, according to our measurements in this region of the retina, the after-image and the contrast excitations from white are more intensive than those from black, the quality of the screen and

preëxposure designed to give dark contrast must be regulated until the brightness excitation aroused is found to be equal in amount to the white given by the black screen and preëxposure. A series of these changes can be made until a point is reached where the sensations are reduced in intensity sufficiently to allow the more saturated dark color to be seen farther out than the light color. The sum, then, of the amounts of white and black added in turn to the stimulus, will give the range of brightness change that may be made in a stimulus of full intensity without causing the difference in brightness to be a factor influencing color limits. (*b*) Equal sectors of white and black may be added to the stimulus color until a point is reached where the darkened color is seen farther out than the lightened. This method has the disadvantage that with each addition to the brightness sector, there is a corresponding subtraction from the color sector. On the other hand, however, it may have a possible advantage over the former method in that the brightness excitation that is added to the color is aroused by light-waves, as is the case with the standard colors whose brightness differences gave rise to our problem; hence any theoretical questioning is obviated as to the quantitative equivalence of the action of a brightness excitation objectively aroused to an excitation aroused as after-image or contrast. But since we can not work with colors at full saturation, the disadvantage is probably much in excess of the advantage. We can doubtless come much closer to the value we are seeking by the first method. As the work by this method is not completed, its report will be deferred until a later paper. The results obtained by the second method are given in Table IV. In this table we have shown how much the colored sector may be reduced by the addition of black and white, without changing the limits for the darkened and the lightened color. If a further reduction is made, the darkened color will be seen at a greater excentricity than the lightened color. The results show that 240° of black, white, or gray of the brightness of color may be added to yellow and the limits for the three shades of color so formed will still coincide; 225° to red; 215° to blue; and 230° to green. Since, roughly speaking, the amount of inhibition will be inversely proportional to the amount of color

present, it is obvious that if the colors could have been maintained at full intensity, as they usually are in the investigation of sensitivity, a still greater brightness change would have been possible. While we may not have determined by this method just how much brightness difference there may be between colors at full saturation without affecting the limits, we have shown beyond doubt that there may be much more than is found between the standard pigment colors.

Table IV gives some of the results of this investigation for Observer *A* in the temporal meridian. Each observation was taken with screen and preëxposure card of a gray of the brightness of the color. Since the results in the nasal meridians are very similar to these, space will not be taken to report them. As the sensitivity of the retina falls off gradually in all directions until within 5° of the limit, the limen at this 5° point is almost identical, whatever the meridian.

Table IV.

A. *Showing how much white, black or gray of the brightness of the color we may add to a colored stimulus and still have a coincidence of limits for the three shades of color, providing the amount of colored light coming to the eye is kept constant.*

Stimulus	Value of colored sector	Value of brightness sector (gray of brightness of color, white, or black)	Limit of sensitivity when color is mixed with gray of brightness of color	Limit of sensitivity when color is mixed with black	Limit of sensitivity when color is mixed with white
Yellow	260°	100°	42°	42°	42°
	180°	180°	40°	40°	40°
	90°	270°	37°	38°	37°
	120°	240°	40°	40°	40°
	105°	255°	39°	40°	39°
Green	120°	240°	30°	31°	30°
	130°	230°	31°	31°	31°
Red	120°	240°	37°	38°	35°
	135°	225°	39°	39°	39°
Blue	135°	225°	48°	48°	43° [20]
	145°	215°	49°	49°	49°

[20] The decided narrowing of the limit of the blue stimulus in this case

But there is more than one kind of problem which deals with peripheral color sensitivity. To avoid any possible misunderstanding of our position, a word may be added to show when it is of advantage and when of disadvantage to equate stimuli in brightness. (*a*) When investigating the limits of color sensitivity and when the brightness of the surrounding field is the same as the brightness of the stimulus color, a brightness equation of the different colors, within the limits we have just determined, is not only unnecessary, but a positive harm. This, moreover, is the proper regulation of the brightness of the surrounding field for all investigations of the relative and absolute limits of sensitivity and of the limens of color at different points on the retina. (*b*) When, however, the brightness of the surrounding field is different from that of the color, the factor of the induction of the screen must be taken into account. Since brightness contrast follows the law that maximal contrast occurs when there is a maximal brightness opposition, different amounts of contrast will be induced across colors of different brightnesses. But under these conditions, only one legitimate problem can arise, namely, to test the effect of the screen. There are two points to this problem. (*i*) Knowledge of the effect of different screens upon the same color may be desired. In this case, the problem of

is due to the following cause. For Observer *A* there is a small spot in the horizontal temporal region of the right eye that is totally insensitive to blue light. This miniature spot of blue-blindness extends from 43° to 47° in the horizontal temporal meridian. Now since the apparent intensity of the sensation aroused by the stimulus composed of 135° of blue and 235° of white was not sufficient to allow the color to be seen on the peripheral side of this blue-blind spot, its limit occurred on the foveal limit of the spot, at 43°. It may be added that spots of this type are not unusual. The writer has found in every eye she has tested one or more spots that are partially or totally insensitive to one color alone. Relative to these blind spots, the following interesting features may be noted. (a) Although totally blind to a given color, they have normal sensitivity to its complementary color. (b) They give a fully saturated complementary-colored after-image of this color to which they are blind. (c) They show the usual cancelling action between the color to which they are blind and its atagonistic color. In short, they seem to be exact replicas in the periphery of the normal eye of the unique type of color-blindness described by Schumann (see Schumann, F. Ein ungewöhnlicher Fall von Farbenblindheit. Bericht über die 1. und 2. Kongress für experimentelle Psychologie, 1904, pp. 10-13.

brightness equation would not arise. (*ii*) Knowledge of the effect of the same screen on different colors, or of the comparative effect of different screens on more than one color may be desired. In this case the colors may or may not be equated in brightness:—the question depending upon the requirements of the problem. If they are not equated in brightness, there will be different amounts of induction with each screen for each color. If they are, the colors will be altered in intensity and often in color tone. No general rule can be laid down as to equation or non-equation in these cases. Each has to be settled on its own merits and in accord with the requirements of the problem in hand. What we wish to emphasize more than anything else at this point is that, while at different times in color work, one may need to make legitimate use of a surrounding field which differs in brightness from the stimulus color, it should never be done in any investigation of the relative or absolute limits or limens of color sensitivity. The use of the perimeter and the dark-room is a notable instance of the violation of this precaution. The surrounding field of intensive blackness induces a different amount of white over each of the colors unless they are of the same brightness. And if they are equated in brightness, all the disadvantages which, as pointed out earlier in the paper, result from this equation, are suffered in the investigation. Moreover, to equate the stimuli in brightness is not to get rid of the induction of the surrounding field. We still have, after equating, a large amount of brightness induction which operates against a determination of absolute limits by tending to narrow the limits of sensitivity for all colors; and against a determination of relative limits by narrowing the different colors unequally, depending upon the difference in the inhibitive action of the same amount of white upon them.

2. *Brightness of the Field Surrounding the Stimulus.*

When a small color stimulus is surrounded by a large field of white or black, a sensation is given which consists of the color mixed with black or white, due to contrast induction from the surrounding field. The influence of the brightness of the surrounding field upon color sensitivity resolves itself, then, into the

question of the fusion of colored with colorless light sensation in central or peripheral vision, according to the part of the retina that is stimulated. The details of this fusion in central vision have been taken up by the writer working in collaboration with Dr. C. E. Ferree,[21] in which work it was shown that the effect of fusing a colored sensation with white, black, or gray is twofold. (*a*) There is a quantitative effect due to the inhibition of chromatic excitation by achromatic. White inhibits color most, the grays in order from light to dark next, and black the least. The records of all the observers used in this investigation show that the achromatic series inhibits red and yellow considerably less than blue and green. (*b*) There is also a qualitative effect. The tone of certain colors is changed by the action of the achromatic excitation. The change is greatest when the stimuli are blue and yellow.[22] Yellow, when mixed with black, gives a sensation of olive-green; and blue when mixed with white, black, or gray gives a sensation of reddish-blue.

As a factor influencing the limits and limens of the sensitivity of the retina to color, the inhibitive, or quantitative effect of the fusion concerns us more than the qualitative. As we have stated, a white surrounding field, for example, a white campimeter screen, induces black across the stimulus which fuses with and modifies the resulting sensation; while a black screen induces white. For an estimate of the amount of brightness contrast that is induced by white and black screens across yellow, green, red, and blue stimuli, the reader is referred to the section: *Quantitative Estimate of the Influence of the Change of Illumination upon the Induction of Brightness by the Surrounding Field* (p. 138). The question is considered in detail in that section rather than in the present one, because it will be necessary at that point to compare the amounts of brightness induced by the white and

[21] Ferree and Rand. An Experimental Study of the Fusion of Colored and Colorless Light Sensation: The Locus of the Action. Journ. of Philos. Psychol. and Scientific Methods, 1911, VIII., pp. 294-297. This is only a brief preliminary report of the work. A full report will be published later.

[22] How far the qualitative effects of the fusion of colored with colorless light sensation in central vision are paralleled in peripheral vision, will form the discussion of a later chapter of this investigation, not reported in this paper.

black screens at standard and decreased illumination. In that section is shown also in what way the amounts of brightness induced by the screens were estimated, and within what limits the values obtained can be said to represent these amounts. Tables XII and XIII (pp. 142-143), columns 1, 2 and 3, give the amount of contrast that is induced by the white and black screens at standard illumination across the grays of the brightness of the colored stimuli at 25° and 40° in the horizontal temporal meridian for Observers *A* and *C*. The results of these tables may be summarized as follows:

1. The amount of induction from the white and black screens increases with the distance from the fovea.

2. The amount of induction from the white screen is greater than that from the black screen.[23]

3. The white and black screens induce most across the stimuli that are farthest removed from them in brightness, and least across those which are nearest to them in brightness. That is, the white screen induces more black across the gray of the brightness of blue than across the gray of the brightness of yellow; the black screen induces more white across the gray of the brightness of yellow than across the gray of the brightness of blue.

The effect of this induction of the surrounding field may be shown by two methods: (*a*) by its effect on the limits of color sensitivity; and (*b*) by its effect upon the limens of color sensitivity.[23a] Up to this time, so far as the writer knows, the effect of the surrounding field has been estimated only by the first of these two methods, by its effect on the color limits. This method, however, estimates the effect of the surrounding field upon the color sensitivity of the extreme peripheral retina alone. By the

[23] See footnote p. 141.

[23a] Since sensitivity to color is measured by determining both the limen and j. n. d. of color, it might be thought that the effect of surrounding field could be measured in both of these ways. The determination of the j. n. d. would, however, show very little, because the induction of the surrounding field would affect both the standard and comparison surfaces. This will be true also of the effect of the brightness of the preëxposure, and of changes in the general illumination. In none of these cases has the writer considered it worth while to make the determination of the j. n. d.

second method, on the other hand, this effect can be measured in the central and paracentral regions, as well as in all parts of the peripheral retina. In order to make a complete study of the effect of the brightness of the surrounding field on color sensitivity, we have used both of these methods. The report of the work done by them is as follows:

a. The effect of the induction of the surrounding field upon the limit of color sensitivity.

Assuming that the law of brightness inhibition of color for the central retina holds for the peripheral retina, we should expect to find that, since colors have a lower limen in black than in gray or white, a white screen, which causes black induction across the stimulus, would be more advantageous to color vision than would a black screen, which causes white induction. Further, we should expect to find that a gray screen of the brightness of the stimulus, which causes no induction whatever, would be the most favorable.

An investigation of the color limits with screens of white, black, and gray of the brightness of the color, shows, however, the following facts:

1. Blue and green have widest limits with the gray screen, slightly narrower with the white, and narrowest with the black.

2. Red and yellow have widest limits with the black screen, slightly narrower with the gray, and narrowest with the white.

The color limits of Observers *A* and *C*, taken on the temporal and on the nasal meridian, are given in Table V and VI.

b. Explanation of the effect of the induction of the surrounding field on the limits of color sensitivity.

Turning to the explanation of these results, we shall here endeavor to account for the results obtained with the white and black screens. We have the following points to explain: (*a*) Blue and green have wider limits with the white screen than with the black, but the difference is comparatively small. According to the law of the action of white and black on colors, formulated from the results of work in the central retina, we should expect to find wider limits with the white screen, which induces black, than with the black screen, which induces white. Thus far, then, the results are in accord with the law, but the difference found

TABLE V.

A. *Showing the limits of color sensitivity with screens of white, black and gray of the brightness of the color.*

Stimulus	Limit with gray screen of the brightness of the color	Limit with white screen	Limit with black screen	Meridian
Yellow	44°	42°	45°	90° Temporal
Green	37°	36°	34°	
Red	43°	42°	44°	
Blue	53°	50°	49°	
Yellow	90°	88°	92°	90° Nasal
Green	64°	62°	60°	
Red	89°	87°	89°	
Blue	92°	92°	92°	

TABLE VI.

Observer C.

Yellow	49°	46°	50°	90° Temporal
Green	44°	42°	40°	
Red	45°	41°	45°	
Blue	56°	55°	53°	
Yellow	92°	92°	92°	90° Nasal
Green	87°	84°	53° [24]	
Red	92°	92°	92°	
Blue	92°	92°	92°	

between the inhibitive action of white and of black in the central retina would lead us to expect a greater effect on the limits. (*b*) Yellow and red have wider limits with the black screen than with the white. This is in direct contradiction to the law of fusion formulated for the central retina. With regard to explanation, two points must be considered. (1) The relative inhibitive action of black and white upon color must be investigated in peripheral vision; and (2) the rate of falling off in sensitivity of the peripheral retina must be ascertained.

[24] In this case, the qualitative change of green to blue caused the decided narrowing of the limit.

(1) *The relative inhibitive action of black and white upon color in peripheral vision.* The relative inhibitive action of white and black upon the colors must be investigated at all points from the fovea to the limits of sensitivity to see whether the law established for the central retina holds for all degrees of excentricity. If we find that the difference between their inhibitive actions lessens as we go towards the limits, we have a reason for the small widening of the zones of blue and green by the white screen. And if we find just within the limits of sensitivity for red and yellow that black inhibits these colors more than white does, we have a reason for the relative widening of the zones of sensitivity for these colors with the white screens, provided we can show that the effect of neither screen will carry the limits farther towards the fovea than the inner margin of this zone within which the exception is found.

To test the relative inhibitive power of black and white in the peripheral retina, the limen of color in black and white had to be determined. Two methods of procedure were possible with the apparatus used. By the first method, the stimulus was a disc with sectors of color and white or black which could be adjusted so that a liminal sensation of color was produced. In order to prevent brightness induction the screen had to be of a gray of the brightness of the stimulus used. With each addition of color to the stimulus, a change of the brightness was produced. The screen then had to be altered in brightness by an equal amount. Of the two methods of determining the brightness of the stimulus, described p. 91, the method of comparing the brightness of the colorless peripheral sensation with the surrounding field was obviously better adapted to the requirements of this observation than was the more cumbersome flicker method because the brightness of the stimulus was being continually altered. For the present case, the gray squares were used for surrounding field that had served a similar purpose for the determinations of the brightness of the stimuli in the periphery at standard and decreased illumination. The observer first made a preliminary judgment of just noticeable color, and then determined the gray that was equal in brightness to the stimulus. A square of this gray was then

mounted on the campimeter and the final determination of the limen was made. By the second method, the screens were removed and the skeleton apparatus alone was used. A disc composed of white and black sectors was placed on the motor so that it just filled the large circular ring at the center. This gave a surrounding field whose brightness could be adjusted at will. A small disc, 2 cm. in diameter, composed of sectors of the color to be investigated and black or white, was placed over the large black and white disc. The method of procedure was as follows. The observer took the required fixation, and observed the small disc to find the smallest amount of color that could be sensed when fused with white or with black, as the case happened to be. Before each determination, the experimenter adjusted the black and white sectors of the large disc, so that they equalled the brightness of the inner disc. This brightness was readily calculated from the following quantities:—the number of degrees in the colored sector, its black-white-value, and the number of degrees of white or black in the remainder of the disc.

Since the point in question was of considerable importance, both of these methods were used, the one as a check on the other. The first had the advantage of greater ease of manipulation and of employing a stimulus which was the same size as that used in the sensitivity experiments. The second had a possible advantage in the adjustment of the brightness of the surrounding field, but it was of disadvantage because the surrounding field could not be made so wide as by the former method and because a stimulus larger than that usually employed had to be used.

Results from both of these methods show the following facts: (1) As the fixation becomes more excentric, the difference in the inhibitive action of white and black decreases. (2) From center to periphery, the limens of green and blue are greater when mixed with white than when mixed with black; that is, the law of the greater inhibitive power of white holds for these colors in the periphery as well as in the center. (3) An exception to this law is found for yellow and red near the limits of sensitivity. From the center to within about 5° of the limit of sensitivity,[25] white

[25] By the limit of sensitivity is meant the widest limit of color determined at standard illumination.

has a greater inhibitive power than black over these two colors. But from this point to the limit, the reverse relation obtains, and red and yellow in this region have a greater limen in black than in white. How much this apparent exception to the law of fusion as it obtains in central vision is due to the natural darkening of red and yellow as they pass into the peripheral field of vision, we are not at this time prepared to state. Because of this darkening, there is more black fused with red and yellow than the results of Table VII express. These results represent the values of the colored and black sectors in the stimulus discs only and not the actual proportions of color and black excitations aroused.

Results are shown in detail in Table VII. They are taken from the records of Observer *A*, on the temporal meridian by the first method described. Column 1 indicates the stimulus used; column 2, the fixation at which the liminal determination was made, and columns 3 and 4, the limens of color mixed with white and black.

TABLE VII.

A. *Showing the inhibitive action of white and black upon color in peripheral vision.*

Stimulus	Fixation	Limen of color in white	Limen of color in black
Yellow	0°	40°	3°
	35°	85°	65°
	38°	95°	85°
	40°	120°	115°
	42°	290°	320°
Green	0°	45°	5°
	25°	80°	50°
	31°	130°	100°
	33°	200°	175°
Red	0°	30°	3°
	35°	80°	65°
	38°	120°	110°
	39°	135°	135°
	40°	155°	170°
	42°	290°	310°
Blue	0°	60°	10°
	35°	125°	65°
	41°	145°	140°
	42°	180°	170°
	51°	300°	280°

(2) *The rate of falling off in the sensitivity of the retina to*

color from center to periphery. To determine the falling off in sensitivity of the retina, the limen of color must be known at several points of excentricity. For this determination, the results given in Table VIII, which shows the limens of color when the brightness influence of the screen has been eliminated, best serve our purpose. They show that at 5° from the limit, the limen has been increased from three to tenfold as compared with the limen at 25°, or six to fourteenfold as compared with the limen at the center. The distance between the point 25° from the center, and the point 5° inwards from the limit averages for all colors about 10°. It is readily seen that the sensitivity falls off much faster from the point 25° from the center to 5° from the limit than it does from the center to the 25° point. At the point 3° inwards from the limit, the limen ranges from 145° of color, in the case of blue and green, to 150° of color, in the case of yellow and red. It is from this point that the sensitivity falls off with extreme rapidity. As was mentioned earlier in the discussion (see p. 105), a change in the fixation of 1° peripheralwards causes an increase in the limen of 65° or more, an increase that represents a greater lessening of sensitivity in 1° of excentricity than there was in the first 25° from the fovea.

Values of the limen for all colors with gray screens of the brightness of the color at 0° and 25° from the center, and 5°, 3°, 2°, and 1° from the limit are shown in Table VIII. They were determined in the temporal meridian of Observer *A* and are selected as typical. An equal zone of rapidly decreasing sensitivity was found on the nasal meridian also in every case where the limit of color sensitivity occurred within the range of our apparatus.

In Tables V and VI, it was shown that the limits of color are not changed more than 5° with the white and black screens from their values with screens of the brightness of the color used. The results of Table VIII show why this is so. The comparatively large amounts of induction by the white and the black screens narrow the limits so little because of the extreme rapidity with which sensitivity falls off in this zone. To narrow the limits even 3°, enough brightness must be induced, roughly speaking, to completely inhibit more than 200° of color.

TABLE VIII.

A. *Showing the rapid falling off in sensitivity of the extreme peripheral retina.*

Stimulus	Limen at 0°	Limen at 25°	Limen 5° from limit	Limen 3° from limit	Limen 2° from limit	Limen 1° from limit	Limit
Yellow	18°	35°	100°	150°	240°	330°	44°
Green	20°	40°	130°	145°	260°	345°	37°
Red	9°	17°	132°	150°	200°	320°	43°
Blue	9°	12°	130°	145°	200°	310°	53°

The following points, then, needed in our explanation of the influence of the white and black screens on the limits of color sensitivity have been established. (*a*) The white screen, which induces black, narrows the limits of sensitivity to red and yellow more than the black screen, which induces white, because neither screen narrows the limit more than 5°, and within this zone of 5°, red and yellow are inhibited by black more than by white. (*b*) The limits of blue and green are narrowed by the black screen more than by the white screen, because within this zone of 5°, as at the center, these colors are inhibited more by white than by black. But they are narrowed less by the black screen than might be expected from the inhibitive action of white found to obtain at the center, because as we go towards the periphery, the difference between the inhibitive actions of white and black decreases. And (*c*) neither screen narrows the limits for any color more than 5°, because within the zone 5° from the limits, the sensitivity falls off so abruptly from point to point that more brightness action is required to change the limits beyond this amount than either the white or the black screen induces.

We have explained the limits of sensitivity to the four colors when black and white screens are used. We have still to explain the results obtained with the gray screen. Since it causes no brightness induction, we might expect our widest limits to occur with this screen. Table V and VI, however, show that while this is true to some extent for blue and green, it is not true for red and yellow. The limits for red and yellow with the gray screen

of the brightness of the color are in each case slightly narrower than with the black screen and wider than with the white. As we are still working on this point, we do not at present feel justified in saying anything final by way of explanation. We may point out, though, that red and yellow darken in passing into the peripheral field of vision. The black screen tends to lessen this effect by contrast, and the white screen to augment it. It seems reasonable to expect, then, that the black screen, which lessens, by means of the white contrast, the amount of black fused with these colors in darkening, would widen their limits; and that the white screen, which increases it by means of black contrast, would narrow their limits, as compared with the gray screen, which exerts no effect at all. We can speak only tentatively, however, until the amounts of brightness dealt with in each case can be more accurately ascertained.

C. *The Effect of the Induction of the Surrounding Field upon the Color Limens.*

In order to estimate the effect of the induction of the surrounding field upon the limen of sensitivity to the different colors, the limens of color were determined at the center, and at 15°, 25°, and 30° of excentricity in the peripheral retina (*a*) when the surrounding field was of the gray of the brightness of the color; (*b*) when it was white; and (*c*) when it was black.

The preëxposure was in each case to the gray of the brightness of color. The limen was determined as follows: The stimulus composed of sectors of the color and the gray of the brightness of the color at the excentricity for which the limen was to be determined, was placed on the motor behind the campimeter screen. The proportions of the sectors were changed until the observer made the judgment of just noticeable color. Judgments were taken in ascending and descending series, and the average was taken as the value of the limen.

The results show that the influence of the brightness of the surrounding field upon the color limen is as follows:

1. The limen is lowest when the surrounding field is of the gray of the brightness of the color.

2. The difference in the effect of the white and black screens upon the limen increases from the fovea outwards.

3. For yellow and green the limen is highest when the field is black and the induction white, and lower when the field is white and the induction black.

4. For red and blue, the limen is highest when the field is white and the induction black, and lower when the field is black and the induction white.

5. The difference in the effect of white and black screens on the limens is not so great as one at first thought might be led to expect from the results obtained by the objective mixing of white and black with color in the central retina.

The results for Observer *A* are given in detail in Table IX.

D. *Explanation of the Effect of the Induction of the Surrounding Field upon the Color Limens.*

We have, then, the following facts to explain: (1) The limen of sensitivity to color is lowest when the surrounding field is of the gray of the brightness of the color. This is what should be expected, because in case of this screen there is no induction present to fuse with the color sensation, and to affect the limen of sensitivity. (2) The difference in the effect of the white and black screens increases from the fovea outwards. This is because the sensitivity of the retina to brightness contrast increases from the fovea outwards, as the table for the amounts of induction shows. More white and black, then, are induced, and as our results with objective mixing show, the greater are the amounts of white and black mixed with color, the greater is the difference between the inhibitive actions of equal amounts of each.[26] (3) The limen of sensitivity to yellow and green is high-

[26] A rough demonstration of this can be easily made as follows. Set up two discs, of blue for example, side by side on color-mixers. Add a small sector of white to the one and an equal sector of black to the other, and observe the apparent saturations of each. Repeat the observation several times, each time increasing the sectors of black and white by equal amounts. It will be observed that the difference in the apparent saturations of the equally saturated discs becomes greater and greater, until at 180° the disc to which white was added appears almost colorless while the disc to which black was added is still a well-saturated dark blue.

est when the surrounding field is black, and lower when the surrounding field is white. This is in accord with the general law of the inhibitive action of white and black on color. That is, since color is inhibited less by black than by white, we should expect in terms of the law that the limen of color would be lower with the white screen which induces black than with the black screen which induces white. The limens obtained for yellow and green present no exception to this law. (4) The limens for red and blue are highest when the surrounding field is white, and lower when the surrounding field is black. But this is in apparent contradiction to our general law of the relative inhibitive action of white and black upon the colors. An explanation of why we have this apparent contradition in case of red and blue and not in case of yellow and green may be readily found, however, in the relative amounts of contrast induced by the white and black screens across these colors. Table XII (p. 142) shows the amount of contrast that is induced by the white and the black screens across the grays of the brightness of the colors. As we have already mentioned, the white screen induces more black across the grays of the brightness of red and blue, than of yellow and green; the black screen induces more white across the grays of the brightness of yellow and green, than of red and blue. For example, Observer *A* estimated the amount of black induced by the white screen at 25° in the horizontal temporal meridian as 135° for yellow, and 155° for green; and the amount of white induced by the black screen as 110° for yellow, and 60° for green. There is, then, less white induced across these two colors by the black screen than there is black induced by the white screen. In spite of this, however, the greater inhibitive power of this smaller amount of white is sufficient to raise the limen of sensitivity to yellow and green slightly higher than it is raised by the less inhibitive power of the larger amount of black. For red and blue, on the other hand, the black induced by the white screen is estimated as 230° for red, and 290° for blue; while the white induced by the black screen is estimated as only 28° for red and only 12° for blue. In these cases there is a very much greater amount of black induced than of white.

And this very much greater amount of black is sufficient to raise the limen of sensitivity to the colors with which it is fused higher than it is raised by the very small amount of white, in spite of the fact that when equal amounts of black and white are mixed with a color, its saturation is inhibited much more by white than by black. (5) The difference in the effect of white and black screens on the limens is not so great as one at first thought might be led to expect from the results obtained by the objective mixing of white and black with color in the central retina. This may be explained as follows. (1) The relative amounts of white and black induced upon the different colors by the screens vary greatly. We have thus not a simple case of a difference in the inhibitive action of equal amounts of black and white. In case of yellow and green, for example, there is so much more black induced than white that the white raises the limen very little more than the black. And in case of red and blue, the amount of black induced is so very much in excess of the white that the limen is raised even more by the black than by the white. It is not raised much more, however, (even less than the excess for white in case of yellow and green), because (*a*) the excess of black induction is not sufficiently large greatly to overweigh the superior inhibitive power of white; and (*b*) the difference between the inhibitive powers of white and black is high for red and blue, especially for blue. (2) The difference in the inhibitive power of white and black on colors decreases from the center to the periphery of the retina. Thus not so great a difference is found in the limens for white and black screens in the peripheral retina as one might be led to expect from the amounts of induction present. An inspection of the table shows that the difference in the limens for the white and black screens increases from the center towards the periphery, but this increase caused by the greatly increased amounts of induction[27] is not so great as it would have been, were there no decrease in the difference in the inhibitive power of white and black on the different colors.

[27] It has already been shown, footnote, p. 121, that the greater are the equal amounts of white and black added to color, the greater will be the difference in the inhibitive actions exerted by these equal amounts.

Table IX

A. *Showing the limens of color sensitivity with screens of white, black, and gray of the brightness of color.*

Stimulus	Point on horizontal temporal meridian at which limen was taken	Limen with screen of gray of brightness of color	Limen with white screen	Limen with black screen
Yellow	0°	18°	22°	28°
	15°	22°	25°	35°
	25°	35°	50°	65°
	30°	50°	80°	95°
Green	0°	20°	22°	28°
	15°	27°	30°	35°
	25°	40°	50°	75°
Red	0°	9°	13°	10°
	15°	9°	19°	15°
	25°	17°	30°	23°
	30°	25°	50°	29°
Blue	0°	9°	17°	10°
	15°	10°	25°	12°
	25°	12°	35°	18°
	30°	20°	40°	30°

We have explained the effect of the induction of the surrounding field on the limits of color sensitivity, and on the limens of sensitivity. As we have said, the effect on the limit takes place in the extreme peripheral retina; the effect on the limen has been measured in the more central regions of the retina,—at 0°, 15°, 25°, and 30° of excentricity. We have remaining to compare the effect of the induction of the surrounding field in the extreme peripheral retina, as estimated by the limit, with its effect in the more central regions, as estimated by the limen, and in turn to determine how both sets of effects harmonize with our law of the inhibitive action of brightness on the colors. The comparison of the results obtained by the two methods for each of the colors is as follows:

1. For yellow, the limen of sensitivity was lower with the white screen but its limit was wider with the black screen. The effect of the screen upon the limen for this color is in accord with our general law of the relative inhibitive action of white and black upon the colors; and the effect of the screen on the limit

is in accord with its exception formulated for the extreme peripheral retina; that is, that in the region 5° from the limit for yellow, black inhibits yellow more than white does.

2. For green, the limen was lower and the limit was wider with the white than with the black screen. The effect of the induction of the screens, then, on both limens and limits, is in accord with our general law.

3. For red, the limen was lower and the limit was wider with the black than with the white screen. The effect of the induction of the screens on the limen is not in accord with our general law that white inhibits color more than black; however, the exception is readily explained by the much greater amount of black than of white that is fused with the color sensation by the induction of the screens. The effect on the limit is in accord with our exception to this law formulated for the extreme peripheral retina; that is, that within the region 5° from the limit of sensitivity to red, black inhibits red more than white does.

4. For blue, the limen was lower with the black screen, but the limit was wider with the white screen. The effect of the induction of the screen on the limen is not in accord with our general law, but the exception may be explained, as in case of red, in terms of the very much greater amount of black induced by the white screen than of white induced by the black screen. We have here, however, an apparent paradox with regard to the limits. That is, since the law of the relative inhibitive action of white and black is the same at the limit for blue as it is at the center, we might expect that if the black induction was sufficiently in excess of the white to make the limens higher for the white screen than they were for the black, it would also correspondingly make the limits narrower for the white screen than for the black. The reverse, however, it will be remembered, was true. The reason for this lies in the fact often mentioned previously that blue lightens in the periphery, so that near its limit of sensitivity it is not in so much greater contrast to the white screen than to the black screen as it is in the center. For example, for Observer *A* the brightness of blue in the periphery

equalled gray No. 28. In the periphery, then, the amount of white induced by the black screen is sufficient to inhibit the blue sensation more than it is inhibited by the amount of black induced by the white screen. It may be mentioned, however, that the difference between the limits for blue with the white screen and with the black screen is smaller for all observers used than is the difference between the limits with these screens for any other color with which we worked (see Tables V and VI, p. 114).

3. *The Brightness of the Preëxposure.*

When making the color observation in the peripheral retina, the observer is given a short period of preparation before the stimulus is exposed, in which to obtain and hold a steady and accurate fixation. This introduces the factor of preëxposure, for during this period of preparation, the area which is to be stimulated by color receives a previous stimulation. It seems strange to the writer that this factor, which exerts a greater influence over the extent of color sensitivity than any we are examining, with the possible exception of large changes in the general illumination, should have been so generally overlooked in the work of earlier investigators. It has always been considered a sufficient precaution to eliminate all color from the preëxposure. This, however, is not enough. It should also be of the same brightness as the color by which the eye is to be stimulated. If not, it gives an after-image which mixes with the succeeding color sensation and both reduces its saturation and modifies its color tone.[28] If the preëxposure is lighter than the stimulus color, it adds by after-image a certain amount of black to the succeeding color impression; if darker, it adds a certain amount of white. Since white inhibits color more than black, the effect of a dark preëxposure is to reduce the sensitivity to color more

[28] This action takes place apparently at some physiological level posterior to the seat of the positive, negative, and contrast color processes commonly supposed to be located in the retina. (See Ferree and Rand. An Experimental Study of the Fusion of Colored and Colorless Light Sensation: The Locus of the Action. Journ. of Philos. Psychol. and Scientific Methods, 1911, VIII., pp. 294-297.)

than the effect of a light preëxposure.[29] But since both white and black as after-effect reduce the sensitivity to color, the eye is rendered more sensitive when no after-image is given, that is, when the preëxposure is of the same brightness as the color. The preëxposure should, therefore, be to a gray of the brightness of the color. No brightness after-image will be added to the succeeding color impression to modify either its saturation or its color tone. Even closing the eye, as is frequently done before stimulating, is equivalent to giving a black preëxposure.

No thought apparently was given by previous experimenters to the intense after-effect which follows the exposure of the eye to a brightness quality differing from that of the stimulus. Hess,[30] Fernald,[31] and Thompson and Gordon,[32] it is true, covered the stimulus before exposure with a card matching in quality the campimeter screen, but since the campimeter screen was not always of the same brightness as the color used for the stimulus, this by no means ruled out the effect of preëxposure. The motive of each of these experimenters seems to have been to standardize the observation for the effect of preëxposure, but no notion of its action sufficiently clear to guide them in formulating their technique seems to have been entertained. Since the action of the preëxposure is by way of arousing a brightness after-image, it is obvious that the preëxposure card should, as stated above, be matched in brightness to the stimulus color rather than to the screen.

In the articles, *"Colored After-Image and Contrast Sensa-*

[29] A very striking demonstration of the effect of preëxposure upon the sensitivity of the retina to color can be made for class or lecture room purposes as follows. Mount a sheet of the blue paper of the Hering series on cardboard. Cover one-half of another sheet of cardboard of the same size with white of the Hering series of papers, the other half with velvet black. Place this card immediately in front of the first card and fixate its center for 10 or 15 seconds. Remove and observe the comparative effect of the white and black preëxposures thus obtained upon the color impression gotten from the blue surface.

[30] Hess, C. loc. cit.

[31] Fernald, G. M. Psychol. Rev., 1905, XII., p. 394; Psychol. Rev. Monog. Sup., 1909, X., No. 42, p. 17.

[32] Thompson and Gordon. A Study of After-images on the Peripheral Retina. Psychol. Rev., 1907, XIV., p. 123.

tions from Stimuli in Which No Color Is Sensed,"[33] and *"The Fusion of Colored with Colorless Light Sensation.—The Physiological Level at Which the Action Takes Place,"*[34] the effect of the after-image due to previous brightness exposure upon color sensitivity has already been shown for both central and peripheral retina. The general fact need not further be dwelt on here. We do, however, need to show why in the peripheral retina the short preëxposure which takes place while the eye is obtaining a steady fixation has so much effect upon the color stimulation immediately following. Two reasons are found for this. (*a*) The peripheral retina is extremely sensitive to short stimulation. While some slight variation is found at different angles of excentricity, the peripheral after-image reaches in general its maximal intensity with two or three seconds stimulation. This amount of time is usually consumed in obtaining fixation, hence in each observation there is fused with the color sensation about as strong a brightness after-image as can be aroused. For this reason alone, it is readily seen why the brightness of the preexposure is of so much greater consequence in the peripheral retina than it is in the central retina, where the maximal strength of the after-image is obtained with from forty to sixty seconds stimulation. (*b*) There is apparently no latent period in case of the peripheral after-image. It flashes out at full intensity immediately upon the cessation of the stimulus. Thus, there is no possibility of escaping the full effect of the brightness after-image upon the stimulus color, as might happen in the central retina, where the latent period obtains, if there were a very short exposure to the stimulus color.

If when working with the campimeter, for example, a black card is used to cover the stimulus-opening during the period of preparation, an intensive white after-image is aroused which

[33] Ferree and Rand. Psychol. Rev., 1912, XIX., pp. 195-239.

[34] For abstract of the article, see Journ. of Philos. Psychol. and Scientific Methods, 1911, VIII., pp. 294-297. The article will soon be published in full. See also Ferree, C. E. Tests for the Efficiency of the Eye Under Different Systems of Illumination and a Preliminary Study of the Causes of Discomfort. Transactions of the Illuminating Engineering Society, 1913, VIII., pp. 40-60.

fuses with the succeeding color sensation, strongly reducing its saturation. If, on the other hand, a white card is used, a black after-image is obtained, which, according to our law of the action of the achromatic sensation upon color, has less effect than the white after-image upon blue and green, and also upon red and yellow if the after-image is sufficiently strong to narrow the limits to red and yellow more than 5°. In each case, the intensity of the after-image will in part depend on the brightness of the subsequent color exposure, the projection field. The after-image due to preëxposure to white will be more intensive when blue than when yellow forms its projection field. The after-image from black will be more intensive when projected on yellow or green than on blue or red. If, however, a gray card of the brightness of the stimulus color be used as preëxposure, there will be no after-image to modify the color sensation. The only brightness change acting upon it will be due to the slight adaptation to this gray during the short time of preëxposure.

The method, then, of eliminating the effect of preëxposure consists in making it of the brightness of the color to be used as stimulus. And in case the brightness of the color alters in passing from the center to the periphery of the retina, the brightness of the preëxposure must be correspondingly altered. For example, at standard illumination, Hering Gray No. 41, or its equivalent should be used for preëxposure to blue when the central retina is investigated. But for the peripheral retina, a much lighter gray should be used because in this region blue lightens by an amount depending upon the excentricity of the stimulation and in part upon individual variation.

A. Effect upon the Limens of Color and upon the Limits of Color Sensitivity.

To test the importance of preëxposure, two methods of measurement were employed. In the first, the limen of color was obtained at 0° and at 35° on the temporal meridian, when the screen was of the gray of the brightness of color, and the preëxposure was in turn to the same gray, to white, and to black. In the second method, the limits of color sensitivity were investigated under the same conditions of campimeter

screen and preëxposure card. The results for Observer *A* are recorded in Table X and in rows 1, 4, 7, 10 of Table XI. They show in every case, (*a*) that the limen is raised and the limit is considerably narrowed when the preëxposure is not to the gray of the brightness of the color, that is, when it gives a brightness after-image; and (*b*) that the limen is higher and the limit narrower when the preëxposure is to black and its after-image is white, than when the preëxposure is to white and its after-image black.[35] This is in accord with the law of the

[35] There is one exception to this statement. The limen for blue at 0° for both white and black preëxposures is 13°. The following reasons may be given for this. (a) It is one of the fundamental laws of brightness after-images that the intensity of the after-image depends in part upon the brightness relation of stimulus to projection field. When the brightness difference between the stimulus and the projection field is small, a weak after-effect is obtained; when it is greater, a more intensive after-effect is obtained. Blue, as aroused in the central retina, is very near to black in brightness, and very far removed from white. We should then expect a very much more intensive after-effect of the exposure to white than to black when the projection field is blue. (b) The brightness relation of the surrounding field to the preëxposure also exerts an effect on the intensity of the after-mage given by the preëxposure. When the surrounding field differs in brightness from the preëxposure, contrast is induced. This contrast quality in turn also gives an after-image which mixes with and modifies the after-image given by the preëxposure. When the surrounding field is of the gray of the brightness of blue, for example, and the preëxposures are in turn white and black, the influence of the surrounding field is to make the after-image of white stronger than that of black. That is, when the preëxposure is white, this white is strongly intensified by contrast with the surrounding field of dark gray, and in consequence the black after-image is strongly intensified. But when the preëxposure is black, little intensification results by contrast with the surrounding field and little effect is had on the after-image. Both of these influences, then, tend to cause much more black to be added to a blue stimulus in the central retina as a result of preëxposure to white than white to be added as a result of preëxposure to black. The effect of this excess of black, as is shown by the table, is to raise the limen for blue for the white preëxposure as much as it is raised by the black preëxposure; in other words, to make the limens equal. At 35° in the periphery, however, the limen of blue is seen in the table to be higher when the preëxposure is to black and the after-image white, than when the preëxposure is to white and the after-image black. We have here a different case. The difference in the effect of white and black preëxposures at 0° and at 35° is due to the fact that at 0° blue is very dark while at 35° in the periphery it has lightened until its brightness equals No. 35 gray. In the latter case (a) there is less difference than there was at 0° between the brightness relations of the stimulus to

action of brightness upon color and holds for all colors used. It might be expected from the exception to this law, mentioned on page 116, that the limits for red and yellow would be narrowed more by the black after-image than by the white. This is not found to be true because the effect of each after-image is sufficiently strong to narrow the limits of red and yellow more than 5°, and thus to carry the limits for these colors outside of the zone in which they are inhibited more by black than by white.

B. Combined Effect of Surrounding Field and Preëxposure upon the Limits of Color Sensitivity.

The effect of preëxposure upon color limits was also investigated when white and black screens were used. The results obtained are of interest in two regards. (*a*) They show under these typical conditions in what way and to what extent the inductive action of the screen combines with the effect of preëxposure to modify the limits of color. (*b*) They help to explain some of the conflicting results obtained by previous investigators who did not carefully standardize their observations with reference to the effect of preëxposure and surrounding field. A few points may be noted in advance of the tables showing the combined action of preëxposure and surrounding field upon the extent of color sensitivity. It is obvious that when the campimeter screen is either white or black and the preëxposure is to the same brightness quality, there will be no inductive

the white preëxposure and of the stimulus to the black preëxposure, and consequently less difference between the intensities of the after-images from these preëxposures; and (b) there is less difference than there was at O° between the brightness relations of the surrounding field, which is of the brightness of blue at the point at which we are working, to the white preëxposure and of the surrounding field to the black preëxposure, and for this reason also, less difference between the intensities of the after-effect of the contrast induced by the surrounding field upon these preëxposures. For both reasons, therefore, the after-image from the white preëxposure at 35°, when projected on blue, is not so much more intense than the after-image from the black preëxposure, as it was at O°. At 35°, then, in these experiments the white after-effect due to preëxposure to black is sufficiently intensive to raise the limen of blue higher by virtue of its greater inhibitive power than it is raised by the black after-image due to preexposure to white.

action by the screen upon the preëxposure either to intensify or to weaken it. In this case both preëxposure and screen will add the same brightness quality to the stimulus color, the former by contrast, and the latter by after-image. The effect of this action upon the color limits is shown in Table XI, Column 4, rows 2, 5, 8, 11; and column 5, rows 3, 6, 9, 12. If, however, the preëxposure and the screen are different in quality, their action may be either antagonistic or supplementary, depending upon the brightness relations between the screen and the preexposure, on the one hand, and between the screen and the color sensation fused with the after-image of preëxposure on the other. For example, if a black preëxposure and a white campimeter screen are used, the white screen will intensify the blackness of the preëxposure by contrast but will tend to darken the fusion of color sensation and white after-image, and thus will lessen the action of the latter upon the color. This effect is shown in Table XI, in column 4, rows 3, 6, 9, 12; and column 5, rows 2, 5, 8, 11. If, however, the preëxposure is black. and the campimeter screen is the gray of the stimulus color, the

TABLE X.

A. *Showing the effect upon the color limens of preëxposure of the gray of the brightness of the color used, of white, and of black.*

Stimulus	Surrounding field	Preëxposure	Limen at 0°	Limen at 35°
Yellow	gray no. 2	gray no. 2 white black	18° 35° 45°	83° 105° 125°
Green	gray no. 8	gray no. 8 white black	20° 33° 40°	100° [36] 155° 180°
Red	gray no. 24	gray no. 24 black white	9° 13° 20°	90° 135° 148°
Blue	gray no. 41 at 0° no. 35 " 35°	gray white black	9° 13° 13°	30° 40° 43°

[36] As green has a narrow zone of visibility, the limen was taken at 30°.

creen will intensify the blackness of the preëxposure by contrast, ut will lighten the fusion of stimulus color and white after-mage, thus will add to the action of the latter upon the color. This effect is shown in Table XI, columns 4 and 5, rows 1, 4, ', 10.

TABLE XI.

A. *Showing the combined effect of campimeter screen and reëxposure upon the limits of color sensitivity.*

Stimulus	Campimeter screen	Limit with gray preëxposure of the brightness of the color	Limit with white preëxposure	Limit with black preëxposure
ellow	gray no. 2	44°	40°	38°
	white	42°	42°	43°
	black	45°	43°	40°
reen	gray no. 8	37°	35°	31°
	white	36°	30°	25°
	black	34°	36°	25°
ed	gray no. 24	43°	38°	37°
	white	42°	38°	39°
	black	44°	43°	38°
lue	gray no. 28	53°	42° [37]	42° [37]
	white	50°	42° [37]	48°
	black	49°	51°	42° [37]

Having seen from Tables X and XI the effect of preëxposure nd the combined effect of preëxposure and surrounding field pon the limen and the limits of color, we may turn our attention o a third point of interest; namely, the explanation of some f the differences between our results and those obtained by arlier investigators in terms of the different conditions of pre-xposure used. As Hess and Fernald alone have stated their onditions of preëxposure, we shall have to limit our discussion o them. Hess wished to find the comparative limits of color ensitivity. He attempted to standardize the intensity and the rightness of the stimuli used, and worked with white, black, nd gray campimeter screens. The eye of the observer followed

[37] For the explanation of this decided narrowing of the limit for blue, see ootnote, p. 108.

a moving fixation-point while the stimulus was exposed from time to time. In every case, the stimulus was covered by a card of the same brightness and quality as the screen. He turned the gray screen toward or away from the source of light until its brightness was such that the color disappeared in the periphery into a gray of the brightness of the screens. He thus worked with screens of the gray of the brightness of the color, of white, and of black, and with preëxposures of the same brightness as the screens. In only one of these cases, namely, the first, has he eliminated the effect of preëxposure. He found that for every color, the limit of sensitivity was widest with the gray screen, narrower with the black, and narrowest with the white. His results are in contradiction to ours with regard to the influence of these screens, when the factor of preëxposure is eliminated (see p. 113). They are, however, very nearly confirmed by the results we obtained when the preëxposure was of the same brightness as the screen (See Table XI). Had our illumination been slightly less, and consequently the induction from the white screen greater, our results would have been very similar to those of Hess.

Fernald, working with a white and a black background and using preëxposures to match, obtained results that are similar to those of Hess for all colors except red, and even in this case the exception is only apparent. She says: "All the colors except the reds are perceived at a greater degree of eccentricity with the dark than with the light background. Red is seen as red to about the same degree of eccentricity with the dark as with the light background, but is seen as yellow or orange with the dark background at the same points at which it is seen as colorless with the light background."[38] The latter part of the quotation shows that the exception to Hess in case of red was due rather to a difference in the method of measurement than to a difference in result. She recorded as the limit of color the point at which the sensation took on any trace of a foreign quality. Although the red stimulus appeared as red-yellow in the periphery with the black screen, there was some red in the

[38] Fernald, G. Psychol. Rev. Monog., 1909, X, p. 23.

sensation received from it at a greater angle of excentricity with the dark than with the light screen.

As was said above, the conclusion of Hess and of Fernald that the colors have wider limits with the black than with the white screen, is confirmed by our work at certain illuminations when white and black preëxposures are used. But, since we do not obtain similar results when the influence of preëxposure is eliminated and the effect of the brightness of the field determined in isolation from this factor, we maintain that their results were due to brightness conditions not connected with the surrounding field, but with the preëxposure. Our contention is that many of the conflicting conclusions concerning the effect of background upon color limits have resulted from ignorance of the important factor of preëxposure. Comparative color limits can be obtained with any screen only when the preëxposure is to the gray of the brightness of the stimulus. This principle was used by Hess in his work with the gray screen, but apparently without a definite purpose and without knowledge of its importance.

4. *The General Illumination of the Retina.*

The effect of change of illumination was forced upon our attention early in the investigation of the factors that influence the color sensitivity of the retina. For example, in preliminary work done by the writer on a well-lighted porch on Long Island, changes in color tone were reported, when certain colors were compared in the central and in the peripheral retina, that are not found at all under the more intensive illumination of our optics-room, when neither of the curtains is drawn; and the peripheral limits of color were narrower by 5° to 12°. Furthermore, on a dark day, it was found that the limits of stimuli exposed through an opening in a white screen were reduced by about 4° as compared with the limits taken on a bright day The change was less considerable with black and gray screens. The change in color tone was most conspicuous in case of green.[39] On dark days the green stimulus appeared as a pale unsaturated blue before becoming colorless in passing from the center to the periphery of the retina. This zone of blue was from 7° to 23°

[39] The green of the Hering series was used.

wide in different meridians of the retina with both white and black screens, but was wider with the black than with the white screen. On a sunny day, on the other hand, with the white screen green passed into bluish-green, then directly into gray, except in case of the upper regions where it appeared blue throughout a zone of about 4° in width. With the black screen, the blue zone was found only in the upper and temporal regions of the retina. The transition of green to yellow in the periphery that is generally reported in the literature was found in these experiments only when the gray screen was used. Yellow showed a color change that varied in amount with the degree of the general illumination. On a bright day, it appeared reddish-orange with the white screen. On a cloudy day, it was seen in the extreme periphery as a dark saturated red.

Working in our optics-room we found also that results taken on one day could not at all be duplicated on the following day. When the work was carried on under the most favorable conditions without special means of controlling illumination, namely, on bright days only, differences of 5° or more were found when the white screen was used. This necessitated a long series of observations if legitimate averages were to be obtained. Such a procedure is at best a poor makeshift and is besides of great disadvantage in many problems that come up in the work on color sensitivity. Particular instances of this may be found in investigations in which it is required to work in the region lying just within the limits of sensitivity, and in work on the after-images of stimuli in which no color is sensed. In the latter case the experiment requires that the stimulus be exposed just outside the limits of sensitivity determined with a given brightness condition, and that the observer should not be aware of the nature of the stimulus. In order to fulfill these requirements the experimenter must know the limits obtaining with a given brightness condition. It would be impossible to know this when the brightness conditions were subjected to the influence of changing illumination unless re-determinations were made at the beginning of each sitting and even frequently during its course. This would consume a great deal of time and would, besides,

only roughly fulfill the requirements of the problem. A further and still more important example of the disadvantage may be found in the task we had set ourselves, namely, to investigate from point to point the sensitivity of the retina to each of the principal colors for three backgrounds in at least sixteen different meridians. In this work it is obvious that unless a standard illumination were provided, all comparative work would have to be done at one sitting. This is impossible. When time is taken between observations to guard against fatigue, at least three hours is required merely to outline the limits of sensitivity for a given color with one background for only one-half of the retina. Even for this length of time there is no guarantee that the illumination has not altered. Thus at the outset of any extended investigation of color sensitivity, it is evident that without a standard illumination, results will be of little comparative value.

In order better to know our factor and the ways in which it operates, a systematic investigation of the influence of changes of general illumination was carried on in our optics-room, which is especially constructed to secure fine changes in illumination. Rough preliminary experiments showed that the primary effect of decreasing the illumination was an alteration of the amount of contrast induced across the stimulus by the campimeter screen. With the white screen, the increased induction was the most pronounced and was sufficient to cause large changes in the limits and in the color tone of the stimulus. In order to investigate this effect in detail, gradual changes of illumination covering a wide range were made by means of the curtains with which our optics-room is furnished, described on p. 86. Attention was given to the following points. (*a*) A quantitative estimate was made of the influence of change of illumination upon the brightness induction of the campimeter screen. (*b*) The effect of this induction upon the limits of color sensitivity was determined. (*c*) The limens of the colors were measured at different degrees of excentricity at different illuminations. And (*d*) the influence of change of illumination upon the effect of the preëxposure on the limens and limits of color was investigated. The degrees

of illumination chosen for comparison were the standard illumination, the method of obtaining which will be described later, and the decreased illumination mentioned above (see p. 95 and Tables I and II) for which the white-values of the stimuli were determined. Measured in foot-candles by means of the Sharpe-Millar portable photometer, the standard illumination equalled 390 foot-candles, the decreased 1.65 foot-candles.

A. Quantitative Estimate of the Influence of Change of Illumination upon the Induction of Brightness by the Surrounding Field.

The purpose of this investigation was to find out how much the induction from white and black screens[40] is affected by a change in the general illumination; and (*b*) how much induction is gotten at decreased illumination from the gray screen which matches the color in brightness at standard illumination. The induction in this latter case is caused by the change in the brightness relation between color and screens with decrease of illumination.[41] The campimeter screens served as inducing surface, grays of the brightness of the four principal colors of the Hering series both at standard and decreased illumination were used in turn as stimuli, and the amount of induction was estimated upon a measuring-disc, made up of adjustable sectors of the gray of the stimulus and white or black, according to the screen used. The measuring-disc was mounted on a motor (see p. 87 and Fig. I) which could be moved along the graded arm of the campimeter to any position from 20° to 92°. The gray stimulus was exposed through the opening of the screen in the usual manner. Two preliminary precautions were observed. (*a*) Since

[40] White and black screens are chosen because they represent the extreme cases of the effect of change of illumination.

[41] This latter determination is made to show that it is impossible to standardize the brightness of the surrounding field against the sudden and progressive changes of daylight that occur during the course of a single series of observations. These changes alter the brightness relation between the colored stimulus and the gray used as screen; therefore a match made at the beginning of a series will not hold throughout its course. For the same reason and to an equal degree the brightness relation between preëxposure and colored stimulus changes with change of illumination. It is, therefore, equally impossible to standardize the brightness of the preexposure without some means of securing a standard illumination.

the brightness of the gray stimulus plus the induction of the screen was to be estimated by means of the measuring-disc, and since the brightness-value of the stimulus and of the disc changes with the amount of light that falls upon them, it was necessary to make sure before each measurement that the same amount of light fell upon each. This precaution was all the more necessary because the stimulus had to be placed behind the screen and the measuring-disc in front. In a given position of the apparatus, one or the other was apt to be shaded. The determination was made as follows: Measuring-disc, campimeter screen, and gray stimulus were all given the same brightness-value according to determinations made under conditions about which no doubt of the equality of the illumination of each could be entertained. Each was then placed in position for the experiment, and the position of the campimeter as a whole and of its various parts was adjusted until stimulus, screen, and measuring-disc were exactly matched in brightness-value. When an exact match was obtained we were guaranteed that all three were again equally illuminated. This precaution was particularly necessary in the investigation we are discussing in this section. It was carefully observed, however, throughout the entire work. (*b*) The question arose whether brightness induction comes to its maximal value at once in the peripheral retina. A determination of the intensity curve of the contrast sensation was accordingly made at various points in the peripheral retina. It showed that contrast increases strongly for the first few seconds of stimulation. For this reason it was found to be necessary to make the judgment concerning the amount of induction of the screen, just as long after the induction had commenced as was done in the experiments to determine color sensitivity. In the color experiments an interval has to be allowed before the stimulus is exposed during which the observer obtains a steady fixation. During this interval of preëxposure, the eye is being stimulated by the campimeter screen and by the card which covers the stimulus. To prevent the preëxposure card from giving a brightness after-image which would fuse with and modify the sensation immediately following, it should be chosen of a gray of the

brightness of the color. In the same way, an interval had to be given in which to secure steady fixation when the amount of brightness induction was being measured. In order, then, to have the judgments made in each case the same length of time after induction had begun it was necessary only to make the intervals of preëxposure of equal duration and to require that the judgments of each kind be made directly at the end of the preëxposure. In the case of the color experiments, the signal for the making of the judgment is the withdrawal of the preëxposure card and the exposure of the stimulus. For the judgments of induction, however, in which case the stimulus was the gray of the brightness of the color, it is obvious that no preëxposure card was needed, for preëxposure and stimulus were required by the conditions of the experiment to be the same. In this case, a word-signal had to be given to indicate the termination of the preëxposure interval and the instant at which the judgment was to be made.

Results when white and black screens were used.—Observing these precautions as to the equality of the illumination of stimulus, screen, and measuring-disc, and as to the length of time the induction had had in which to increase before the judgment was made, measurements were taken on the induction by white and black screens across grays of the brightness of the four principal colors at the illumination used. These measurements were made at various points of excentricity on the retina, and for both standard and decreased illuminations. The determination of the equality point between the stimulus and the measuring-disc was made as follows: The size of the white or black sector of the latter was changed until a preliminary judgment of equality was made. Then the j. n. d. on either side of this point was determined both by ascending and by descending series and an average of the results was taken as the value of the induction. Measurements were taken at 25° and at 40° on the temporal meridian, and at 55° and 70° on the nasal. The conditions at the nasal 55° were very similar to those at 25° on the temporal side. The measurements at 70° nasal were midway in value between those at 25° and at 40° on the temporal. The 40° point is very near the limits of color sensitivity in this meridian, and the induction here is very great. For one of

server, the darker stimuli appeared black at this point, when the white background was used. In such cases, the difference between the induction at standard and at decreased illumination is more clearly shown by the observations made at 25° temporal meridian and at 55° and 70° nasal meridian than at 40° temporal. We have, however, chosen for two reasons to present in the following table only the results obtained in the temporal meridian. (*a*) The results obtained in this meridian demonstrate sufficiently well all the facts that need be taken into consideration. Space will not, therefore, be given to the results for both meridians. (*b*) The second point of our problem requires us to correlate the increased amount of induction caused by a given decrease of illumination with the change in the color limits it produces. The limits of color sensitivity can be more easily investigated in the temporal meridian because the sensitivity to some colors extends in the nasal region beyond the 92° point, which is the limit of measurement for the apparatus we used. This is true in particular in case of Observer *C* as may be seen in Table VI. Both purposes of the investigation are, then, better satisfied by results obtained in the temporal meridian.

The results show in general the following facts.

(1) The amount of induction increases with the distance from the fovea.

(2) The amount of induction increases with decrease of illumination.[42]

(3) The amount of induction from the white screen is greater than that from the black screen.[42a]

(4) The amount of increase of induction at decreased illumination is greater in case of the white screen than in case of the black screen.

(5) The white and black screens induce most across the stimuli that are farthest removed from them in brightness, and least across those which are nearest to them in brightness. That

[42] This statement is meant to apply only to the range of illumination worked with. The induction was not measured when the illumination was very low, nor when it was very intensive.

[42a] An exception to this statement of result occurs in case of gray No. 2 at 40°. This stimulus is so near to white in brightness that the induction across it, according to the principle stated in (5) above, is greater for the black screen than for the white.

is, the white screen induces more black across the gray of the brightness of blue than across the gray of the brightness of yellow; the black screen induces more white across the gray of the brightness of yellow than across the gray of the brightness of blue.

Results are given in detail in Tables XII and XIII. Table XII gives the results for observer *A* taken on the temporal meridian, and Table XIII, the results for Observer *C* for the same meridian. There is some difference in the amount of induction reported by the different observers, but since the preceding general statement of results is clearly borne out in every case, it is not deemed necessary to give space to results from all the observers used. In these tables, column 1 gives the degree of excentricity at which the observation was made; columns 2, 3, and 4, show respectively the stimulus used, and the amounts of induction from the white and from the black screens at standard illumination. Columns 5, 6, and 7, give the same data for decreased illumination.

Table XII.

A. *Showing the amount of contrast induced by the white and the black screens at standard and decreased illumination upon the grays of the brightness of the colored stimuli at standard and at decreased illumination.*[43]

Fixation	Standard illumination			Decreased illumination		
	Stimulus (gray of brightness of each of the four colors at standard illumination)	Amt. induction of white screen	Amt. induction of black screen	Stimulus (gray of brightness of each of the four colors at decreased illumination)	Amt. induction of white screen	Amt. induction of black screen
25°	gray no. 2	Black 135°	White 110°	gray no. 2	Black 220°	White 170°
	gray no. 8	" 155°	" 60°	gray no. 6	" 270°	" 80°
	gray no. 24	" 230°	" 28°	gray no. 41	" 320°	" 40°
	gray no. 37	" 290°	" 12°	gray no. 20	" 330°	" 30°
40°	gray no. 2	" 200°	" 300°	gray no. 3	" 320°	" 360°
	gray no. 8	" 300°	" 132°	gray no. 5	" 360°	" 180°
	gray no. 24	" 360°	" 60°	gray no. 50	" 360°[44]	" 0°
	gray no. 29	" 360°	" 28°	gray no. 13	" 360°	" 100°

[43] It is obvious that the method used in this and the following tables of expressing the amount of brightness induction gives an underestimation

TABLE XIII.

Observer C.

5°	gray no. 2	Black 70°	White 55°	gray no. 2	Black 130°	White 70°
	gray no. 8	" 84°	" 48°	gray no. 6	" 155°	" 59°
	gray no. 24	" 93°	" 30°	gray no. 40	" 187°	" 45°
	gray no. 37	" 160°	" 15°	gray no. 17	" 244°	" 22°
0°	gray no. 2	" 110°	" 200°	gray no. 3	" 216°	" 340°
	gray no. 7	" 142°	" 160°	gray no. 4	" 230°	" 320°
	gray no. 24	" 180°	" 95°	gray no. 50	" 360°“	" 0°
	gray no. 29	" 214°	" 35°	gray no. 7	" 300°	" 108°

Results when the gray screen matching the colored stimulus in brightness at standard illumination is used. It was necessary to perform the experiments bearing on this point at decreased illumination only. For them the campimeter screens which matched in brightness the four principal colors of the Hering series at standard illumination served as inducing surfaces. For

Suppose, as is shown in Table XII, that No. 24 Hering gray has been darkened by induction until it matches in brightness a disc made up of 230° of black and 130° of the No. 24 gray. The amount of induction is greater than is represented by the 230° of black because the induction has not lessened the amount of light coming to the eye from the gray paper while the addition of 230° of black to the measuring-disc has cut off approximately ⅔ of the light coming from the gray paper. That is, in the one case enough black has been added by induction to reduce 360° of No. 24 gray to the given point in the brightness scale, while in the other enough black was added by direct mixing to lower only 130° of No. 24 gray to this point in the scale. Moreover, the underestimation will be increased by this method of measuring in proportion as the amount of induction is increased because the greater the induction is the more black and the less gray will have to be used in the measuring-disc. All that can be said accurately is that a certain gray darkened or lightened by induction matches in brightness a gray made up of a certain amount of the given gray plus a certain amount of black or white. The exact amount of the induction can not be separated out. Further just because the brightness added by contrast does not alter the amount of light coming to the eye while the brightness added in any method of measurement does change this amount of light, the writer knows of no way by which an exact expression can be obtained. The method she has used, however, does serve as a means of comparing the amounts of induction occurring under different conditions sufficiently accurately for her purpose at this point.

“ The gray No. 50 was in reality rendered blacker by the inductive action of gray No. 24 than the Hering black we used on the measuring-disc. A match thus could not be attained with black 360° as the table indicates.

the contrast surfaces, grays of the brightness of these colors at decreased illumination were chosen. The methods of measuring, precautions in working, parts of the retina investigated, etc., were the same as in the preceding determinations. The following general statement of results may be made.

1. At the 25° point the brightness of yellow was found not to have changed at all with the decrease of illumination produced by changing the illumination from the value selected as standard to the value selected for the comparison; the brightness of green lightened by an amount equal to the difference between No. 8 and No. 6 of the Hering series of grays; red darkened by an amount equal to the difference between No. 24 and No. 40; and blue lightened by an amount equal to the difference between No. 32 and No. 20. The amount of induction by the gray screen of the original brightness of the color upon the gray stimulus of the brightness of the color as altered by the decreased illumination, expressed in terms of Hering white and black, was for yellow 0°, for green 60° of white, for red 27° of black, and for blue 20° of white.

2. At the 40° point, the yellow darkened by an amount equal to the difference between No. 2 and No. 3 of the Hering grays; green lightened by an amount equal to the difference between No. 8 and No. 5; red darkened by an amount equal to the difference between No. 28 and No. 50; and blue lightened by an amount equal to the difference between No. 28 and No. 13. The amount of induction produced by these changes was for yellow 280° of black, for green 130° of white, for red 360° of black, and for blue 60° of white. These results are shown in detail in Table XIV.

(B.) *The Effect of These Amounts of Induction upon the Limits of Color Sensitivity.*

In order to obtain an estimate of the range of effect upon the limits of color sensitivity of the induction of the screens at standard and at decreased illumination, the breadth of the color zones was determined at both illuminations (*a*) when white and black served in turn as campimeter screens; and (*b*) when a gray matching the color in brightness at standard illumination was

TABLE XIV.

A. *Showing the amount of contrast induced at decreased illumination on grays of the brightness of the colors at decreased illumination by the gray screens matching the colors in brightness at standard illumination.*

Fixation	Stimulus	Screen	Amount of Induction
25°	gray no. 2	gray no. 2	0
	gray no. 6	gray no. 8	white 60°
	gray no. 41	gray no. 24	black 27°
	gray no. 20	gray no. 37	white 20°
40°	gray no. 3	gray no. 2	black 280°
	gray no. 5	gray no. 8	white 130°
	gray no. 50	gray no. 24	black 360° [45]
	gray no. 13	gray no. 29	white 60°

used. The preëxposure was in each case to gray of the same brightness as the stimulus at the illumination used.

Results when white and black screens were used. When the stimulus color is gotten by reflection from a pigment surface, two factors operate to give a change of result when the illumination is decreased. (1) There is a decrease in the amount of colored light coming to the eye. (2) There is an increase in the inductive action of the screen due to the change in the brightness relation of the stimulus to screen and to the increased sensitivity of the eye to brightness contrast at decreased illumination.

In order to find out how much of our results with the white and black screens should be attributed to the decrease in the amount of colored light coming to the eye produced by the decreased illumination, and how much to the increased inductive actions of the screens, the limits of sensitivity were also determined at both illuminations with the screens of the gray into which the color disappears in the peripheral retina. From the values obtained with the three screens at both illuminations, the amount of change due to decrease in the amount of colored light coming to the eye and the amount due to induction by the white and black screens were calculated as follows. (*a*) From

[45] The gray No. 50 was in reality rendered blacker by the inductive action of gray No. 24 than the Hering black we used on the measuring-disc. A match could not be thus attained with black 360° as the table indicates.

the number of degrees expressing the limits for a given color at standard illumination with a screen of the brightness of the color at that illumination was subtracted the number expressing its limit at decreased illumination, with a screen of the brightness of the color at the decreased illumination. That this gave the number of degrees the zone of sensitivity was narrowed by the decrease in the energy of the stimuli, may be said with the following qualification. If there is any influence upon color sensitivity of the local brightness-adaptation of the retina produced by the change in the general illumination, it is, of course, included in this effect. But, since this influence would have to be brought about by previous exposure to the illumination in question, it can be reduced to a minimum by guarding against an exposure to it for any considerable length of time. The effect of whatever adaptation there may be, however, can not be isolated or separated out from the above result, and the value expressing the amount the limit is narrowed by the actual decrease of the energy of colored light coming to the eye cannot, strictly speaking, be obtained. But it is probable that the adaptation effect is not sufficiently strong to influence the limits, since the sensitivity of the extreme peripheral retina falls off very abruptly from point to point. The difference, then, between the color limit obtained at standard illumination and the limit at decreased illumination, when in both cases there is no brightness induction from the screen, may be said to approximate the effect upon the limits produced by the decrease in the amount of colored light coming to the eye. (*b*) Figures can be obtained, however, from our results, which express the amount by which the zones are narrowed by the change in the inductive action of the white and black screens produced by decreasing the illumination, that are not open to theoretical questioning; for the influence of local brightness-adaptation, if there be any, is a constant for all screens at the same illumination. If then, the number of degrees which expresses the limits of sensitivity for either the white or the black screen at decreased illumination is subtracted from the number expressing the limit with a screen of the gray of the brightness of the color at this illumination, the result will rep-

resent the extent to which the limit was narrowed by the action of induction alone.

The results show in general the following facts:

1. At standard illumination, induction from the white screen narrows the limits of yellow and red; induction from the black screen narrows the limits of blue and green. The difference is in no case more than 4°.

2. At decreased illumination, the induction from the white screen narrows the limits of all the colors much more considerably than does the induction from the black screen.[46]

3. The values expressing the narrowing of the limits caused by decrease of illumination without induction, are greatest in case of those colors which undergo maximum change of brightness in passing into the periphery, namely, for blue and red.

We have shown by the results of the preceding section, that the increased induction produced by decrease of the general illumination is greater for the white screen than for the black, and, by the results of this section, that this increase is effective to the extent of narrowing the limits of sensitivity to all colors from 5° to 13° with this screen. With the black screen, the limits were narrowed from 0° to 6°. At standard illumination, the limits were narrowed only from 1° to 4° with either the white or the black screen.

Results in detail are given in Tables XV and XVI taken from the temporal meridians of the observers whose observations are recorded in Tables XII and XIII. In column 1, Tables XV and XVI, is given the stimulus. Column 2 shows the limit of sensitivity to the stimulus at standard illumination with a screen of a gray of the brightness of the color at standard illumination; column 3 shows the limit with a white screen; and column 4 with a black screen. Column 5 shows the limit at decreased illumination with a screen of the brightness of the

[46] For Observer *A* the results for green present an exception. At the decreased illumination used the green stimulus appeared bluish in the central retina. The induction of the black screen caused it to appear as a pale blue at a comparatively slight degree of excentricity. According to our definition of color limit, this point is the limit of green. It is, however, obvious that the exception is due rather to the qualitative than to the quantitative effect of brightness upon color.

color at decreased illumination; column 6 shows the limit with a white screen; and column 7 with a black screen.

TABLE XV.

A. *Showing the color limits at standard and decreased illumination (a) with gray screens of the brightnesses of the colors at the illumination used; and (b) with white and black screens.*

Stimulus	Standard Illumination		Decreased Illumination			
	Limit with gray screen of brightness of color at standard illumination	Limit with white screen	Limit with black screen	Limit with gray screen of brightness of color at decreased illumination	Limit with white screen	Lmit w black sc
Yellow	44°	42°	45°	43°	35°	43°
Green	37°	36°	34°	36°	31°	27°
Red	43°	42°	44°	40°	31°	40°
Blue	53°	50°	49°	49°	36°	43°

TABLE XVI.

Observer C.

Yellow	49°	46°	50°	46°	36°	44°
Green	44°	42°	40°	41°	28°	33°
Red	45°	41°	45°	41°	34°	41°
Blue	56°	55°	53°	50°	38°	44°

Tables XVII and XVIII to show the following facts:

(*a*) How much the decrease of illumination narrowed the limits of color sensitivity by causing a decrease in the energy of the light-waves coming to the eye. This was determined by subtracting the value of the limit at decreased illumination with the screen of a gray of the brightness of the color at decreased illumination from its value at full illumination with the gray screen of the brightness of the color at full illumination. (*b*) How much the limits were narrowed by the action of the white and black screens at decreased illumination. This was ascertained by subtracting the values of the limit with the white and the black screen at decreased illumination from the value of the limit at decreased illumination with the gray screen of the brightness of the color at this illumination. (c) How much

more the limits were narrowed by the white and the black screens at decreased than at full illumination. This was computed for the white screen, for example, as follows: The quantity, limit at decreased illumination for gray screen of brightness of color at decreased illumination, minus limit for white screen at decreased illumination, is subtracted from the quantity, limit at full illumination for gray screen of brightness of color at full illumination minus limit for white screen at full illumination. A similar computation was made for the black screen.

Table XVII.

A. *Showing (a) how much the limits were narrowed by decrease in the amount of colored light coming to the eye; (b) how much they were narrowed by increased induction of white and black screens at decreased illumination; and (c) how much more they were narrowed by induction of white and black screens at decreased than at full illumination.*

Stimulus	How much limits were narrowed by decrease in amount of colored light coming to the eye	How much limits were narrowed by induction of white screen	How much limits were narrowed by induction of black screen	How much more limits were narrowed by white screen at decreased than at full illumination	How much more limits were narrowed by black screen at decreased than at full illumination
Yellow	1°	8°	0°	6°	1°
Green	1°	5°	9°	4°	6°
Red	3°	9°	0°	8°	1°
Blue	4°	13°	6°	10°	2°

Table XVIII.

Observer C.

Yellow	3°	10°	2°	7°	3°
Green	3°	13°	8°	11°	4°
Red	4°	7°	0°	3°	0°
Blue	6°	12°	6°	11°	3°

Results when a gray screen matching the color in brightness at standard illumination is used. In these experiments a determination was made of the amount the limits of sensitivity are changed by the brightness induction caused by the alteration of

the brightness relation between stimulus and screen with decrease of illumination, when a screen is used which matches the color in brightness at standard illumination. This determination was made as follows.

An estimate was made of the amount the limits were narrowed by decrease of illumination when a screen of the brightness of the color at standard illumination is used for both standard and decreased illuminations. From this result was subtracted the amount the limits were narrowed by decrease of illumination when the screen is made in turn of the brightness of the color at standard and at decreased illumination. The difference obtained represents the value sought. It is given in Table XIX.

TABLE XIX.

A. *Showing how much the color limits were narrowed at decreased illumination by the induction of the screen which matched the color in brightness at standard illumination.*

Stimulus	Screen of brightness of color at decreased illumination	Limit	Screen of brightness of color at standard illumination	Limit	Amount limit was narrowed by change in brightness relation between stimulus and screen caused by decreased illumination
Yellow	gray no. 3	43°	gray no. 2	41°	2°
Green	gray no. 5	36°	gray no. 8	29°	7°
Red	gray no. 50	40°	gray no. 24	33°	7°
Blue	gray no. 13	49°	gray no. 28	46°	3°

(*C.*) *The Effect of These Amounts of Induction upon the Limens of Color at Different Degrees of Excentricity.*

We have shown the effect of decreasing the general illumination upon the color sensitivity of the peripheral retina with gray, white, and black screens by the effect on the limits of sensitivity. This is only an indirect means of estimating its influence, for the results obtained cannot be translated into terms of direct measurement, owing to the irregular decrease in sensitivity of

the peripheral retina from the fovea outwards. In this section, we shall measure the influence of changes of illumination directly by the changes produced in the limen of sensation at various angles of excentricity. As in the previous section, measurement will be made of the effect upon sensitivity (*a*) of the decrease in the amount of colored light coming to the eye, produced by the decrease of illumination, (*b*) of the difference in the inducing power of the white and black screens, and (*c*) of the change in the brightness relation of stimulus to background.

To determine the first of these three points, a campimeter screen had to be selected that gave no brightness contrast with the stimulus. To provide for differences in the brightness of the colors at the different points observed for the two illuminations at which we worked, a preliminary determination of the brightness of the sensation at these points was made at both illuminations by the flicker method. The brightness of the screen was chosen in each case of the brightness of the color according to these determinations. To eliminate the effect of preëxposure, the stimulus previous to exposure was in every case covered by a gray of the brightness of the color for the illumination used at the point of the retina at which we were working. Thus no brightness after-image was carried over to exert an inhibitive action upon the color sensation. The stimulus was a disc compounded of the sectors of the color, and of the gray of the brightness of the color for the illumination used at the point of the retina under investigation. The proportions of the sectors were altered until the observer gave the judgment of just noticeable color. The average of judgments made in ascending and descending series was chosen as the final value of the limen. The difference between the limens at standard and decreased illumination was taken as the measure of the loss in intensity which the stimulus had sustained by the decrease of illumination.

The effect upon the color limen of the increased induction from the white and black screens was shown by the same method, with the exception that the white and black screens were substituted for the gray of the brightness of the color. The stimulus was a disc composed of sectors of color and gray of the brightness of

the color at the angle of excentricity at which the determination was made.

The effect of the change in the brightness relation between the stimulus color and the screen produced by decrease of illumination was shown as follows. An estimate was made of the amount the limens are raised by the decrease of illumination when a screen was used for both standard and decreased illumination that had a brightness-value equal to the color at standard illumination. From these results was subtracted the amount the

TABLE XX.

A. *Showing how much the limens of sensitivity were raised at the fovea, and at points* 15°, 25°, 30° *from the fovea in the horizontal meridian on the temporal side by the decrease in the amount of colored light coming to the eye produced by the decrease in the general illumination.*

Stimulus	Point on horizontal temporal meridian at which limen was taken	Limen at standard illumination with screen of brightness of color at standard illumination	Limen at decreased illumination with screen of brightness of color at decreased illumination	How much limen was raised at decreased illumination
Yellow	0°	18°	20°	2°
	15°	22°	32°	10°
	25°	35°	40°	5°
	30°	50°	65°	15°
Green	0°	20°	20°	0°
	15°	27°	28°	1°
	25°	40°	50°	10°
Red	0°	9°	11°	2°
	15°	9°	13°	4°
	25°	17°	25°	8°
	30°	25°	45°	20°
Blue	0°	9°	10°	1°
	15°	10°	13°	3°
	25°	12°	15°	3°
	30°	20°	40°	20°

limens were raised by decreasing the illumination when the screens were made in turn of the brightness of the color at standard and at decreased illumination. The difference obtained represents the value sought. These results are of particular importance because they show that the influence of the brightness of the surrounding field can not be eliminated even when a screen of the brightness of the color is used unless some means be had of maintaining the general illumination of the room constant.

Table XX shows how much the limens of sensitivity were raised at the fovea and at points 15°, 25°, and 30° from the fovea in the horizontal meridian on the temporal side by the decrease in the amount of colored light coming to the eye pro-

TABLE XXI.

A. *Showing the color limens at standard and decreased illuminations with white and with black screens.*

Stimulus	Point on horizontal temporal meridian at which limen was taken	White screen		Black screen	
		Limen at standard illumination	Limen at decreased illumination	Limen at standard illumination	Limen at decreased illumination
Yellow	0°	22°	25°	28°	30°
	15°	25°	50°	35°	45°
	25°	50°	80°	65°	85°
	30°	80°	125°	95°	113°
Green	0°	22°	25°	28°	30°
	15°	30°	36°	35°	43°
	25°	50°	75°	75°	220°
Red	0°	13°	20°	10°	14°
	15°	19°	35°	15°	21°
	25°	30°	55°	23°	35°
	30°	50°	330°	29°	58°
Blue	0°	17°	22°	10°	12°
	15°	25°	40°	12°	17°
	25°	35°	60°	18°	25°
	30°	40°	90°	30°	60°

duced by the decrease in the general illumination. The results of this table may be generalized as follows:

1. The limen of color is higher in the periphery than in the center of the retina at both illuminations.

2. The limen of color is higher at decreased illumination than at standard illumination.

3. The direct effect upon the intensity of the sensation produced by decreasing the illumination is shown by the limen determinations to be inconsiderable. In the central retina, the difference is but 1° or 2°. In the peripheral retina at the points considered there is a difference of from 10° to 20°.

Table XXI shows the color limens at both standard and decreased illuminations when white and black screens are used, at the fovea, and at points 15°, 25°, and 30° in the horizontal meridian on the temporal side.

Table XXII has been compiled from Tables XX and XXI to show how much greater the limens were for white and black screens at decreased than at full illumination; how much of the effect may be ascribed to the reduction of the amount of colored light coming to the eye; and how much to the increased induction of the screens. It will be seen from the results of this table that the loss of the sensation in intensity due to the increased brightness induction is much greater than that caused by the reduction in the amount of colored light coming to the eye.

It was shown in Table XIV that quite a great deal of brightness induction is caused by the change in brightness relation between color and screen produced by decreasing the illumination. Table XIX shows how much this induction narrows the limits of sensitivity to the four colors used. Table XXIII, shows how much the limens are raised when the illumination is decreased by the inductive action caused by the change in the brightness relation between stimulus color and gray screen of the brightness of the color at standard illumination.

TABLE XXII.

A. *Showing how much greater the limens were with white and black screens at decreased than at standard illumination and how much of this effect may be ascribed to the reduction in the amount of colored light coming to the eye and how much to the increased inductive action of the screens.*

Stimulus	Point on horizontal temporal meridian at which limen was taken	White screen: Total amount greater	White screen: Amount due to decrease in amount of colored light coming to eye	White screen: Amount due to increased induction of screen	Black screen: Total amount greater	Black screen: Amount due to decrease in amount of colored light coming to eye	Black screen: Amount due to increased induction of screen
Yellow	0°	7°	2°	5°	12°	2°	10°
	15°	28°	10°	18°	23°	10°	13°
	25°	45°	5°	40°	50°	5°	45°
	30°	75°	15°	60°	63°	15°	48°
Green	0°	5°	0°	5°	10°	0°	10°
	15°	9°	1°	8°	16°	1°	15°
	25°	35°	10°	25°	180°	10°	170°
Red	0°	11°	2°	9°	5°	2°	3°
	15°	26°	4°	22°	12°	4°	8°
	25°	38°	8°	30°	18°	8°	10°
	30°	305°	20°	285°	33°	20°	13°
Blue	0°	13°	1°	12°	3°	1°	2°
	15°	30°	3°	27°	7°	3°	4°
	25°	48°	3°	45°	13°	3°	10°
	30°	70°	20°	50°	40°	20°	20°

TABLE XXIII.

A. *Showing how much the color limens were raised at decreased illumination by the induction of the screens which matched the color at standard illumination.*

Stimulus	Point on horizontal temporal meridian at which limen was taken	Limen with screen of brightness of color at decreased illumination	Limen with screen of brightness of color at standard illumination	Amount limen was raised by change in brightness relation between stimulus and screen caused by decrease of illumination
Yellow	0°	20°	20°	0°
	15°	32°	32°	0°
	25°	40°	40°	0°
	30°	65°	116°	51°
Green	0°	20°	20°	0°
	15°	28°	40°	12°
	25°	50°	190°	140°
Red	0°	11°	11°	0°
	15°	13°	24°	11°
	25°	25°	48°	23°
	30°	45°	150°	105°
Blue	0°	10°	12°	2°
	15°	13°	16°	3°
	25°	15°	23°	8°
	30°	40°	55°	15°

(*D.*) *The Influence of Change of Illumination upon the Action of the Preëxposure on the Limens and Limits of Color.*

The brightness of the preëxposure exerts an influence upon the color observation because the eye carries over an after-image from the preëxposure into the color observation. If, for example, the preëxposure is to black, a white after-image is aroused which fuses with the succeeding color sensation and strongly reduces its saturation. The effect of preëxposure is especially strong in the peripheral retina because a very strong brightness after-image is aroused in the peripheral retina by a very short period of stimulation. It is very difficult for the writer to predict from the data she has at hand with regard to the effect of change of illumination upon the sensitivity of the

peripheral retina to the brightness after-image just what will be the effect of change of illumination upon the action of preexposure on the color sensitivity of the peripheral retina. But even though there be no change in the sensitivity of the peripheral retina to the brightness after-image with change of illumination, it is obvious that there will be some effect of the change of illumination because of the change in the brightness relation of the preëxposure card to the colored stimulus. In case the stimulus light is gotten by reflection from pigment surfaces, this change of brightness relation is due to the shift in the brightness of the colors produced by the change in the illumination. In case transmitted light is used as stimulus, the brightness of the stimulus color is independent of changes in illumination and will remain constant; but a change in the brightness relation of stimulus to preëxposure will occur because the preexposure will lighten or darken with change of illumination. The writer hopes to make the quantitative investigation of this point the subject of a future study. At present she can only point out that if a guarantee is wanted that the effect of the brightness of the preëxposure is eliminated from the results of the observation, the preëxposure must be to a gray of the brightness of the color and the illumination of the room must be kept constant.

The foregoing results show how strongly the changes in the illumination of the visual field influence the color sensitivity of the peripheral retina, particularly when the stimulus is surrounded by a white field. They also show that the influence of surrounding field can not be eliminated even by means of a campimeter screen of the brightness of the color unless some means be had of keeping the general illumination of the room constant. It is obvious without further comment how important it is that a method be devised to standardize this factor. The preceding experiments indicate that without this standardization, no experiment can be repeated from time to time under the same conditions relative to any one of the brightness factors that influence color sensitivity. Results thus obtained are far from comparable.

E. *Methods of Standardizing These Factors.*

We have shown in the preceding analysis of the color observation that the factors which influence the limits of color sensitivity, and which, therefore, require standardization, are the brightness of the surrounding field, the brightness of the preexposure, and the general illumination of the retina. Standard conditions require either that the influence of a factor be eliminated, or that it be reduced to a constant. We have been able to treat all three of these variable factors in one or the other of these two ways. The effect of preëxposure and campimeter screen has been eliminated and methods of measuring the general illumination and of keeping it constant have been provided.

As we have seen, the surrounding field influences the color sensation by adding brightness to the stimulus by induction. When, for example, the surrounding field is black, white is induced by contrast across the stimulus color. Since the colors all differ in brightness, the induction takes place in different amounts for the different colors. This white in proportion to its amount reduces the action of the colors on the retina. Further, a given amount of white affects to different degrees the action of the different colors on the retina. The influence of preexposure is even more important than of surrounding field. If the preëxposure is to black, white is added as after-image to the stimulus color. The effect of a black preëxposure upon the stimulus color is greater than the effect of a black surrounding field because more white is added as after-image of preëxposure than is induced by contrast from the surrounding field. Now, since brightness induction is greatest when there is maximal opposition between the inducing and induced fields, and since the brightness after-image also is most intensive when there is maximal opposition between the stimulus and the projection field, it is evident that no one screen nor preëxposure can be found that will influence each color by an equal amount. The black preëxposure and surrounding field concomitant upon work in the dark-room can be considered no exception to this statement. The influence of preëxposure and surrounding field can not be successfully eliminated in work in the dark-room. By

using one screen and preëxposure standard conditions of contrast induction and brightness after-image can be maintained only if the colors are made of equal brightness. The objections to this procedure were pointed out in an earlier section. There remains the alternative of choosing in each case gray papers of the brightness of the colored stimulus for the screen and the preëxposure. This necessitates changes of screen and of preexposure for each stimulus, but insures the complete elimination from the color excitation of all brightness influence due either to preëxposure or to stimulation of the surrounding retina. In this way alone, then, may a proper regulation of these factors be obtained for any investigation whatsoever of the sensitivity of the peripheral retina. Further, the method gives a proper basis with regard to these two important factors from which to start all investigations of the effect of achromatic conditions upon color sensitivity.

Standardization for either one of these factors, however, can be accomplished for one degree of illumination only. As the general illumination changes, the relation of the brightness of the preëxposure and of the surrounding field to the brightness of the colored stimulus changes.[47] It is obvious, then, that if standardization is to be accomplished with regard to the influence of either of these factors, some means must be devised of maintaining the general illumination of the retina constant.

In order to obtain a standard illumination, two things are necessary: (*a*) A means of controlling the illumination must be provided, which is sufficiently sensitive to cause small changes. (*b*) A method of measuring the illumination produced has to be devised; at least, a means must be secured for determining when an illumination has been obtained that is equal to a given preceding illumination. We shall first discuss the method of measurement we adopted. As stated earlier in our paper, no

[47] When the colored light used to stimulate the retina is independent of the general illumination, e.g., when it is obtained from the spectrum, from monochromatic sources, or from standard filters, these two factors alone will modify the result of the color observation. If, however, light reflected from a pigment surface be used as stimulus, a change in the illumination will in addition change the amount of colored light coming to the eye.

satisfactory means of determining the amount of daylight illumination in a room has been provided by the physicist, so there is little hope at this time of solving the problem from that side. The brightness induction of the peripheral retina, however, has been found by us to be extremely sensitive to changes in the general illumination. This phenomenon seems to provide us with a sensitive measure of these changes, while, at the same time, it represents the combined effects for sensation of the principal subjective factors that might vary from day to day. To apply the method in its most sensitive form, the inductive power of white was chosen because it is the most strongly affected by illumination changes. For example, when No. 14 Hering gray was used as stimulus and white as campimeter screen, a noticeable change was produced in the induction when the white curtain of the optics-room was pulled forward 1 cm. from a position in which its edge was directly above the long axis of the campimeter. This caused a change in the illumination of the room so small that it could not be directly sensed. Further, at 11 o'clock in the morning of a bright day in September, when a point at 25° on the nasal meridian was stimulated, Observer *A* reported that the white screen induced black across the stimulus No. 14 gray to an amount that caused it to equal in brightness 107° of black and 253° of No. 14 gray; at 2 o'clock of the same day the induction was increased until the No. 14 gray matched 150° of black and 210° of the gray; at 4 o'clock of the same day the No. 14 gray matched 180° of black and 180° of the gray.[48] Working at 25° in the temporal meridian, this observer reported at different times during one day and on different days, the wide variations shown by the following figures: 283° of black, 225°, 145°, 190°, 238°, etc. Observer *C* reported less induction, but her variations from time to time were equally great. At 25° in the temporal meridian, she found at different times 80° of black, 103°, 160°, 175°, etc. After a careful study of the phenomenon with different screens and with different stimuli, the inductive action of the white screen upon a stimulus of No. 14 Hering gray, at 25° in the

[48] This increase in the inductive action of the screen caused by the decrease in illumination, was accompanied by a shrinkage of the zones sensitive to color covering an area of 4 to 6°.

temporal meridian, was found to provide the best means of detecting changes in the illumination of the optics-room. At this point on the retina, the induction was by no means minimal, nor was it sufficiently great to cause the medium gray chosen for our stimulus to appear too dark to give a small j. n. d. of sensation.

The sensitivity of this method of detecting changes in the general illumination was compared with the sensitivity of the Sharpe-Millar portable photometer. In this photometer one of the comparison fields is illuminated by the light of the room and the other by a standard tungsten lamp enclosed in the photometer box. When the room is illuminated by daylight, the field receiving the light of the room is seen as white, while the field lighted by the tungsten lamp appears as a saturated orange. The difference in color between the two fields renders the photometric judgment difficult and makes the instrument very insensitive for daylight tests. For example, our tests showed that by the method for indentifying an illumination described in the text, a change in illumination could be detected which was produced by drawing the white curtain 1 cm. from a position in which its edge was directly above the long axis of the campimeter. But with the receiving surface of the portable photometer in precisely the same position as the stimulus screen of the campimeter, the edge of the curtain had to be moved 11.3 cm. in order that the change of illumination might be detected. Moreover, this amount of change could be detected only in case the photometric field was continuously observed while the curtain was being drawn, in which case the comparison field was observed to become slightly darkened. The judgment was made, then, in terms of a just noticeably different brightness of the field which was illuminated by the daylight, rather than in terms of a disturbance in the brightness-equality of the two fields. When, on the other hand, the judgment was made in terms of a just noticeable disturbance in the equality of the two fields, as the judgment would have to be made if the photometer were to be employed for the reproduction of any former illumination taken as standard, the curtain had to be drawn 44.2 cm. before the change could be detected. This j. n. d. represents an amount of illumination equal to 2.5 foot-candles.

The next step was to procure a means of changing the illumination of the room by very small amounts. This was accomplished by drawing the white curtain (described p. 86) across the skylight above the apparatus. The drawing of this curtain several inches made little difference in the illumination directly observable by the eye, although, as we have said, a change of 1 cm. when the edge of the curtain was directly above the apparatus, produced a noticeable change in the inductive action of the white screen.

Having thus provided ourselves with a means of producing

small changes of illumination and with a method of detecting them, we had in order to complete our work but to choose an illumination for each observer, which could be taken as standard. Since we wished to work on both light days and days of medium darkness, an average had to be chosen as our standard from the measurements obtained on a number of days ranging from light to dark, so that on bright days the room could be darkened, and on dark days it could be lightened until this value was obtained. For Observer *A* an illumination was selected which caused an induction of black across No. 14 gray stimulus viewed at 25° in the temporal meridian to an amount which caused the gray stimulus to equal in brightness 210° of black and 150° of No. 14 gray; for Observer *B* 180° of black and 180° of No. 14 gray; and for Observer *C* 145° of black and 215° of No. 14 gray. The amount of black induction was identified in each case by means of a measuring-disc made up of sectors of black paper and No. 14 gray of the Hering series.

Previous to each series of observations the illumination of the room was changed until the amount of brightness induction was brought to the value chosen as standard. It was tested at intervals during the sitting and was readjusted when necessary. Details of the method of doing this are as follows: When the white screen and the No. 14 gray stimulus had been put in place, the observer took his position and adjusted the fixation-knot in front of the motor for the 25° point on the temporal meridian. The measuring-disc set at the standard value was mounted on the motor. The observer reported whether the stimulus appeared lighter or darker than the measuring-disc, or of a brightness equal to it. If the judgment lighter or darker was given, the curtain was drawn one way or the other until the stimulus accurately matched the measuring-disc in brightness.

This method not only gives a sensitive measure of the changes of illumination of the visual field and a successful means of standardizing the illumination of a room by daylight, but it has in addition advantages for work in psychological optics not possessed by an objective standardization, could that be successfully obtained. The problem of standardization, includes more for the

psychologist than it does for the physicist, for the former has variables to take into account in addition to the changes that may take place in the energy of the stimulus. Even though the illumination of the room be made objectively constant, we should expect variations in the response of the retina to this illumination because of its own changes from time to time. Brightness contrast, for example, might be expected to vary from sitting to sitting even when the stimulus conditions are kept absolutely constant. Two factors would be concerned in these variations: changes in the inducing power of the surrounding parts of the retina, and changes in the sensitivity of the local area. These changes would take place even when the usual precautions known to the experimenter in this field have been observed. Such precautions are commonly limited to fatigue, adaptation, etc. These precautions do not provide for the changes that occur in the retina from day to day. Moreover, they do not adequately guard against a change in a factor, unless some measure of that factor be had. So far as the writer knows, in these general precautions intended to keep the state of the retina constant, no measure of the variable factor has been provided to test the adequacy of the method. The method proposed by us, however, is planned with this in view. It takes into account not only the objective, but the subjective variables, and reduces both to a constant. For example, when No. 14 gray surrounded by the white field is made equal to the measuring-disc composed of 210° of black and 150° of the No. 14 gray for Observer *A,* it means that the observation may be begun with the assurance that the total result of all the factors—the illumination of the room, the local sensitivity of the retina, and the inductive action of the surrounding parts of the retina—is the same as in the preceding observation.

What has just been said should not be considered as more than a general statement of the application of the principles of the method. In actual practice a greater refinement of working may be attained. If, for example, one wishes to use a preëxposure differing in brightness from that of the colored stimulus, and doubts whether a test which covers only the local sensitivity of the retina and the inductive action of the surrounding parts is a

sufficient check upon the after-image sensitivity, he may make his standard include the effect of the preëxposure he wishes to use. In short, if he does not consider adequate the more general test we have described, he may duplicate, in establishing his standard, any combination of brightness factors, due to preëxposure, brightness of screen, or what not, that he may wish to use in his experiment proper.

The test of a method is how well it works. The test of this method is that we shall be able closely to duplicate our results from sitting to sitting regardless of the changes in the outside illumination from day to day or from morning until afternoon. The method stands the test. Long series of observations in the peripheral retina show a very small M. V.—much less even than is shown in the ordinary color observations in the central retina where, as compared with the peripheral retina, the factors extraneous to the stimulus exert little influence.

The following table has been compiled from a number of observations to show the variations in the results of color limens and color limits (*a*) when the general illumination was controlled according to the method described above, and (*b*) when no further precautions were observed than were used by previous investigators. In previous investigations of the color sensitivity of the peripheral retina, care has been taken to work only at the same hours of days that appeared equally bright, or, if on days of different brightness, to make a rough approximation of preceding illuminations by means of curtains without using either a definite standard or means of measuring. For our work with the illumination controlled, the gray of the brightness of the color at the illumination selected as standard was used for the preëxposure and the campimeter screen. For the work without any especial control of the illumination, the gray of the brightness of the color on one of the days selected as typical was used throughout for preëxposure and screen. This gave in the first case complete elimination of the effect of preëxposure and surrounding field, and in the second case elimination as complete as could be gotten without accurate control of the general illumination. Results are given in the table for blue and green only because the sensitivity to these colors is affected most by changes of illumination.

Stimulus	Illumination	Screen and Preëxposure	Variation of limits on different days	Variation of limens on different days
Green	Controlled	Gray no. 8	0°	0° [49]
	Uncontrolled	Gray no. 9	4°-6°	60°-82° [50]
Blue	Controlled	Gray no. 28	0°	2°-3°
	Uncontrolled	Gray no. 30	4°-5°	18°-30°

At the conclusion of a piece of work the object of which has been the elimination of sources of error in one of the oldest and best developed fields of psychological investigation, the following comments having a more general application to other fields in which sensory determinations are required, may be justified. In all sensory determinations, investigators have been very much annoyed by the magnitude of the mean variation that has occurred in their results. This may be due to two sets of factors: errors in the control of the factors that influence the response of the sense-organ, and errors in judgment. To eliminate the latter source of errors, the psycho-physical methods have been devised. Before beginning her attempts to get a better control of the factors that influence the color sensitivity of the retina, the writer had used all the psycho-physical precautions known to her to eliminate errors in judgment, still her inability to reproduce her results rendered in her judgment any accurate investigation of the sensitivity of the peripheral retina hopeless. On the other hand, however, with the control she has been able to get of the factors that influence the sensitivity of the retina to color, and with only a casual observance of psycho-physical precautions, a very close reproduction of results has been rendered possible. With regard to work in the optics of color at least, then, she is forced to conclude that the major source of error is not in the factors that influence the judgment but in those that influence the response of the sense-organ. Moreover, she would suggest that if in other sensory fields more attention were paid to the factors

[49] The limen for green was taken in both cases at 25° on the temporal retina.

[50] The limen for blue was taken in both cases at 40° on the temporal retina.

that influence the response of the sense-organ and relatively less to the factors that influence the judgment, a higher degree of precision may be attained in our methods of working.[51]

[51] For a further discussion of this point, see Ferree, C. E., Transactions of the Illuminating Engineering Society, 1913, VIII.

THE FLUCTUATION OF LIMINAL VISUAL STIMULI OF POINT AREA

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I. Introduction

In a series of articles published 1906-08,[1] the writer reported the results of an experimental study of the phenomena usually attributed to fluctuation of attention. These phenomena, it was claimed, belong to three sense fields: visual sensation, auditory sensation, and cutaneous sensation. The problem was raised, it will be remembered, in 1888 by Nikolai Lange,[2] who gathered together the instances of intermittence of minimal sensations and found for them a common explanation in the conception of an instable or fluctuating attention. The recurrent changes in the limen of sensation producing the intermittence are, he contended, due to involuntary changes in the degree of attention given to the stimulus. Previous to the series of articles mentioned above, two other explanations had also been given: (a) Involuntary changes in the adjustment of the sense organ in case of vision and audition, primarily accommodation in case of vision (Münsterberg,[3]

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[1] C. E. Ferree: An Experimental Examination of the Phenomena Usually Attributed to Fluctuation of Attention, *Amer. Jour. Psychol.*, XVII., 1906, 81-120; The Intermittence of Minimal Visual Sensations, *Amer. Jour. Psychol.*, XIX., 1908, 59-129; The Streaming Phenomenon, *Amer. Jour. Psychol.*, XIX., 1908, 484-503.
[2] N. Lange: Beiträge zur Theorie der sinnlichen Aufmerksamkeit und der activen Apperception, *Philosophische Studien*, IV, 1888, 389-422.
[3] Hugo Münsterberg: Schwankungen der Aufmerksamkeit, *Beiträge zur experimentellen Psychologie*, Freiburg, 1889, 69-124.

Heinrich,[4] and Heinrich and Chwistek);[5] and (b) an overflow of excitation from the circulatory and respiratory centers in the brain (Münsterberg,[6] Lehmann,[7] Slaughter,[8] Taylor,[9] etc.).[10]

In the series of articles mentioned above it was shown on the negative side that in case of vision at least, intermittence cannot be ascribed to any of the previously mentioned causes; and on the positive side that it is a phenomenon of the adaptation and recovery of the sense organ. Intermittence was denied in case of minimal cutaneous sensation,[11] and the

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[4] W. Heinrich: Die Aufmerksamkeit und die Funktion der Sinnesorgane, *Zeitsch, f. Psychol.*, XI., 1896, 59-76; and Ueber die Intensitätsänderungen schwacher Geräusche, *ibid*, XLI., abt. 2, 1907, 57-59; Zur Erklärung der Intensitätsschwankungen eben merklicher optischer und akustischer Eindrücke, *Bulletin International de l'Academie des Sciences de Cracovie*, Nov., 1898, 363-382.

[5] W. Heinrich und L. Chwistek: Ueber das periodische Verschwinden kleiner Punkte, *Zeitsch. f. Psychol.*, XLI., Abt. 2, 1907, 59-74.

[6] *Loc. cit.*

[7] Alfred Lehmann. Ueber die Beziehung zwischen Athmung und Aufmerksamkeit, *Philosophische Studien*, IX., 1894, 66-95.

[8] J. W. Slaughter: The Fluctuations of the Attention in Some of their Psychological Relations, *Amer. Jour. Psychol.*, XII., 1901, 313-334.

[9] R. W. Taylor: The Effect of Certain Stimuli upon the Attention Wave, *Amer. Jour. Psychol.*, XII., 1901, 335-345.

[10] Münsterberg ascribed to this overflow, in case of respiration, an effect on the muscular control of the eye. During inspiration there was more accurate control of fixation and accommodation and during expiration a less accurate control of these adjustments. Lehmann leaves us in some doubt as to just how he believes the effect is produced. He says (op. cit., p. 84): "Wir sahen dass die Reactionen am haufigsten sind in der Nähe des Inspirationsmaximums. Hier ist eben der Blutdruck am grössten, und von diesem Zustand muss angenommen werden, dass er für die psychologische Arbeit des Gehirns günstig sei. Wir wissen ja, dass das Blut, während der Arbeit irgend eines Organes, demselben reichlicher zufliesst. Deshalb ist es höchst wahrscheinlich, dass auch die Arbeit eines Organes erleichtert werde wenn durch irgend eine Ursache eine Vergrösserung des Blutzuflusses herbeigeführt wird." Slaughter and Taylor are inclined to believe that the overflow affects the sensory cells directly. In their experiments a plethysmographic record of the peripheral blood pressure was taken while the fluctuations of the visual stimulus were being observed. They conclude that their results show a coincidence between the maxima of the plethysmographic curve and the phase of visibility of the fluctuation record. Two kinds of maxima are found in the plethysmographic tracing, one due to inspiration and the other forming the crest of a long vaso-motor wave of unknown cause, commonly called the Traube-Hering wave.

[11] In 1907 the experiments in cutaneous sensation were repeated by Geissler (L. R. Geissler: Fluctuation of Attention to Cutaneous Stimuli, *Amer. Jour. Psychol.*, XVIII., 1907, 318-321). A mistake

phenomenon was left open for further consideration in case of auditory sensation. A part of the work done at this time still remains unpublished. Some of it covers points still in dispute. For that reason two articles will be added to the former series. The first is in answer to an article by Heinrich and Chwistek entitled: "Ueber das periodische Verschwinden kleiner Punkte,"[12] and is intended to clear up, if possible, at least so far as the writer's work is concerned, the last point in dispute between the adaptation and accommodation theories. Heinrich and Chwistek maintain that the fluctuation of minimal visual stimuli of point area is caused by periodic changes in the curvature of the crystalline lens and offer their results for stimuli of point area as evidence that the fluctuations of stimuli of all areas are caused by changes in accommodation. In one of the former studies[13] the present writer had worked with stimuli ranging from 2 mm. x 2 mm.—42 cm. x 38 cm. in area. He found that stimuli of these areas fluctuate just as readily for aphakial as for normal subjects, and that changes in accommodation, therefore, can not be considered an essential factor in the production of the phenomenon. It had never occurred to him to work with stimuli of point area. In the present study, however, stimuli

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was made by him in interpreting the writer's method of stimulating the tongue electro-cutaneously that has not yet been corrected. He says, "In repeating Ferree's experiment with electro-cutaneous stimulation of the tongue, we found some difficulty in eliminating the touch, pressure, and taste sensations set up by the electrodes. The best results were obtained by applying a 1% solution of cocaine to the fore part of the tongue, upon which two strips of tin foil (Christmas tree foil), hammered as thin as possible, were laid. The strips were connected with the interruptor of a Du Bois-Reymond induction coil." Christmas tree foil was not used in the original experiments. This material was rejected at once by the present writer as unsuitable. It is much too stiff and gives rise to pressure sensations. Narrow strips of very thin and pliable wrapping foil were used instead. When these were placed on the fore part of the tongue moistened with spittle, the observer was utterly unable to tell whether or not they were in contact with the tongue when the coil was not working. Neither did they under the action of the current give rise to taste sensations. Of the two procedures the writer would prefer the one used in the original experiments. It seems to him obviously better to make the electrodes of wrapping foil than to use the stiffer material and cocainize the tongue into insensibility to contact, more especially since Geissler's observers report that the cocaine itself sets up distracting sensations in the tongue.

[12] W. Heinrich and L. Chwistek: *Zeitschr. f. Psychol.*, XLI., 1907, 39-74.

[13] See An Experimental Examination of the Phenomena Usually Attributed to Fluctuation, 98-108.

of point area have been used. From the results of this study it will be shown that the fluctuations of these stimuli present no especial case; for (a) they occur just as readily for aphakial subjects as for subjects with normal eyes; and (b) identified by the tests used by the writer in his earlier experiments they correspond just as closely to adaptation phenomena as do the fluctuations of stimuli of larger area. In the second paper, work on the fluctuation of auditory stimuli will be reported. In this work the writer has succeeded in getting conditions under which no fluctuations occur, whether the stimulus be tone or noise. His results also enable him to explain without recourse to central factors or the tensor mechanism of the middle ear the fluctuations which do occur under experimental conditions different from those he has used. The completion of these two pieces of work rounds up, so far as the writer knows, all of the outstanding points in his case against fluctuation of attention in its original meaning.

II. The Accommodation Theory

That involuntary changes in accommodation are a factor in causing the fluctuation of minimal visual stimuli was proposed first by Münsterberg in 1889.[14] Münsterberg held that the fluctuation of these stimuli is due to two causes: unsteadiness of fixation and involuntary changes in accommodation. Although different views may be held with regard to the essential physiological and psychological factors in attention, all must agree, he says, that when a visual stimulus is attentively observed the eye is fixated and accommodated so as best to receive the impression on the retina. But this adjustment cannot be uniformly maintained for any length of time. Involuntary changes both in fixation and accommodation occur. These changes weaken and confuse the light impression received on the retina, hence an object just noticeably different from its background will alternately disappear into this background and become distinct from it.

The effect of lapses in accommodation is too obvious, he thinks, to need special explanation. The rays of light are no longer sharply focused on the retina and the image of the object blurs and becomes indistinguishable from its background. For unsteadiness of fixation, however, the case is not quite so clear. The explanation is as follows. Fick, Kirschmann, and others have shown that the sensitivity of the retina to colorless light attains its maximum at a certain

[14] Hugo Münsterberg: Schwankungen der Aufmerksamkeit, *Beiträge zur experimentellen Psychologie, Freiburg*, 1889, pp. 69-124.

distance from the fovea. Thus when the eye loses its fixation, the image of the object fixated travels towards a more sensitive part of the retina. This will cause the image of the rings on the Masson disc, for instance, which in the traditional fluctuation experiment are made just noticeably darker than their background, to lighten and become equal in brightness to the background. This gives the phase of invisibility. When fixation is regained, however, the ring again becomes noticeable. This gives the phase of visibility. These two factors, then, the lightening of the image of the ring due to involuntary changes of fixation and the blurring of its outlines due to involuntary changes in accommodation, should, according to Münsterberg, be considered as the cause of the alternate appearance and disappearance of the rings on the Masson disc which were attributed by Lange to fluctuation of attention. Since the writer has already shown in his first article[15] that involuntary changes in accommodation cannot be considered as an essential factor in these fluctuations,[16] space will be taken here only to point out that changes in fixation should also not be considered essential factors in the sense in which Münsterberg considers them factors. In the first place they could, in any event, have an effect only in case the stimulus was darker than the background. If the stimulus were lighter than the background, the brightening of the image would make it stand out more distinctly from the background than before, instead of causing it to disappear into the background as it is observed to do in fluctuating. Moreover, the explanation can have little or no application to the fluctuation of colored stimuli. Since both of the latter classes of stimuli fluctuate just as readily as the former, the principle can be regarded as having little value for purposes of explanation. And in the second place, this factor could not in all probability even cause the fluctuation of stimuli darker than the background, for the increased sensitivity of the extra-foveal retina would not only cause the ring to brighten, but also the background immediately surrounding it. The effect of the factor would

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[15] See An Experimental Examination of the Phenomena Usually Attributed to Fluctuation of Attention, pp. 84 and 94-96.

[16] In the original article stimuli ranging in area from 2 mm. x 2 mm.-38 cm. x 42 cm. were used. For the writer's observers fluctuations never occurred when a stimulus 38 cm. × 42 cm. or larger was observed at a distance of 1 meter. In the experimental portion of the present paper it will be shown that changes in accommodation are not an essential factor in the fluctuation of stimuli of smaller area than 2 mm. x 2 mm., namely stimuli of point area. Thus with the present paper the demonstration will have been finished for the whole range of areas for which fluctuation occurs.

thus be merely to raise both the gray of the stimulus and of the background in the brightness scale, not to make them equal, unless indeed one were affected more than the other by an amount that would be noticeable in sensation, which can hardly be possible since the difference between them is, to begin with, only just noticeable.[17]

Münsterberg supported his explanation by the following experimental evidence. The norm of the period of fluctuation was established for each of his subjects and the following variations of conditions were made. (1) A "prismatische Lorgnette" which moved the field of vision slightly to one side was placed before the eyes. When this was held steadily in position, the period of fluctuation was affected very little, but when it was removed and interposed every 2 seconds, causing the eye to move quickly to the side to follow the shift in the object fixated, the period was very noticeably lengthened. (2) Involuntary blinking was caused every 2 seconds by means of a sharp sound. Fluctuation was prevented. When the eyes were closed voluntarily every 2 seconds, the same results were obtained. This, Münsterberg thinks, was because of the relief of muscular strain produced by the blinking. That is, as the lids are closed, the eyes move downwards and inwards; as they are opened, upwards and outwards (Bell's phenomenon). This frequent relief from the strain of fixating and accommodating so freshens the muscles, he thinks, and improves their action that disappearance never ensues. (3) The whole apparatus bearing the Masson disc was slowly moved back and forth, up and down, and sidewise. Each movement was executed in 2 seconds. Thus, in order to fixate the moving stimulus, the eye was kept continuously moving. The accommodation was also kept continuously changing. In a companion series of experiments the head was moved slowly from side to side. In this case also, in order continuously to fixate the stimulus the eye was compelled to move.[18] Fluctuation did not occur in either series of experiments. Again Münsterburg thinks fluctuation was prevented because the muscles were kept in such a fresh condition that accurate fixation and accommodation could be maintained throughout the observations. A moment's reflection will show (1) that these assumptions cannot be wholly true. The attempt of the eye to follow the moving stimulus, whether the movement was apparent, produced by the interruption of the "prismatische Lorgnette" or actual, produced by the moving of the apparatus bearing the stimulus, must have resulted in the image falling now to this side, now to that side of the fovea. If so, the fixation maintained was far from accurate.[19]. Likewise when fixation was lost in blinking, it was doubt-

[17] If, for example, one were very much lighter or darker than the other, the greater sensitivity of the extra-foveal retina might affect one more than the other enough to cause a noticeable change in the difference between them, but this can scarcely be assumed to be the case when one is only just noticeably different from the other.

[18] The movement was equal in amount to the movement of the head and in the opposite direction.

[19] This frequent shifting of the image from the position previously occupied by it on the retina would give abundant chance for the adapting retina to recover, and thus in terms of the adaptation theory to explain the absence of fluctuation.

less regained through a series of small oscillatory movements as commonly happens before the eye comes to rest in taking a new position. And (2) even were the assumptions true, the argument is not at all differential for Münsterberg's theory. The same effect on fluctuation would be expected in terms of the adaptation theory. An abundant reason was given for the stimulus never disappearing in the effect of the eye-movement on restoring the adapting retina. Eye-movement, it will be remembered, exerts its effect on adaptation in two ways. There is (a) an indirect effect. As the result of the movement the image falls on a fresh area of the retina and the area previously stimulated is given a chance to recover. (b) There is a direct effect which is much greater than the indirect effect, namely, the influence of eye-movement upon the amount and direction of the lymph streams that are continually moving hither and thither in the retina. A detailed discussion of this effect was given in the writer's earlier work.[20] Eye-movement is thus an essential factor in both theories. The relation to fluctuation ascribed to it in the two theories, however, is very different. In Münsterberg's theory, eye-movement helps to cause the disappearance of the stimulus, while in the adaptation theory it is the most important cause of the reappearance of the stimulus. With regard to the relative merits of these two views, the writer will say that a few minutes' observation of a liminal stimulus should be enough to convince anyone that a voluntary eye-movement, for example, instead of causing the stimulus to disappear, will on the contrary serve to keep it distinct; and, if it has disappeared, will cause it to reappear. For a detailed demonstration that involuntary eye-movement acts in the same way and that it is the chief factor in rendering adaptation intermittent, see the writer's earlier articles "An Experimental Examination of the Phenomena Usually Attributed to Fluctuation of Attention," and "The Intermittence of Minimal Visual Sensations."

Münsterberg also conducted a series of experiments in which a comparison was made of the rate of respiration and fluctuation. The results showed that when the respiration was in short quick gasps, the rate of fluctuation was increased; and when it was slow, the rate of fluctuation was decreased. In explaining this result he attributes to breathing an influence on the muscular control of the eye. With the inspiration there is an increase of the muscular control; and with the expiration, a decrease.

The accommodation factor was next taken up by Pace.[21] Pace compared the fluctuations obtained by his subjects before and after the paralysis of their ciliary muscles by a solution

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[20] See The Intermittence of Minimal Visual Sensations, *Amer. Jour. Psychol.*, XIX., 1908, 112-129; and The Streaming Phenomenon, *Amer. Jour. Psychol.*, XIX., 1908, 484-503.

In the blinking experiment ,in addition to the effect of the accompanying eye-movement, the blinking would have itself produced an effect on fluctuation. That is, the closing of the lid shut off the light coming from the stimulus and gave the adapting retina a chance to recover.

[21] Edward Pace: Zur Frage der Schwankungen der Aufmerksamkeit nach Versuchen mit der Masson's Scheibe, *Philosophische Studien,* VIII., 1893, 388-403.

of sulphate of atropine, and found no significant difference in his results. He concluded, therefore, that changes in accommodation could not be considered as essential to the phenomenon.

The theory, however, would not down. It was revived by Heinrich, and Heinrich and Chwistek in a series of articles extending from 1896-1907.[22] In the article entitled: "Die Aufmerksamkeit und die Funktion der Sinnesorgane," Heinrich establishes the following principles which he considers of importance in explaining fluctuation. (1) When the attention is directed away from optical impressions (a) the lens takes the curvature characteristic of far seeing, and (b) the lines of sight tend towards the parallel position. The demonstration of these principles, however, cannot be considered as having any very direct bearing on the explanation of the phenomenon of fluctuation, for it may very well be conceived that the voluntary direction of attention away from visual impressions would cause changes in the accommodation and fixation of the eye of a magnitude that would be significant, while the involuntary lapses of attention occurring during the prolonged observation of a stimulus would not cause these changes at all. At least for the purpose of explanation of the phenomenon of fluctuation, the demonstration of the former cannot be considered the equivalent of the demonstration of the latter. And (2) when the attention is directed away from all optical impressions, involuntary changes take place in the curvature of the lens. This conclusion is based upon the recurrent changes that take place in the breadth of the pupil and upon the behaviour of images reflected from the anterior surface of the lens. In drawing this conclusion from the first point of evidence, Heinrich obviously assumes a closer connection between the changes in the breadth of the pupil and changes in accommodation than can safely be done. Any one who has studied the reactions of the pupil under a very wide range of conditions can not help but know that this 1:1 correlation does not exist. Moreover, the connection has not been found in a large enough percentage of cases to make it safe, even plausible, to assume that it exists in any situation in which it has not yet been demonstrated. In his second point of evidence, Heinrich does not describe the behaviour

[22] W. Heinrich: Die Aufmerksamkeit und die Funktion der Sinnesorgane, *Zeitschr. f. Psychol.*, XI., 1896, 410-431; Ueber das periodische Verschwinden kleiner Punkte, *ibid,* XLI., 1907, 59-74, und Zur Erklärung der Intensitätsschwankungen eben merklicher optischer und akustischer Eindrücke, *Bulletin International de l'Academie des Sciences de Cracovie,* Nov., 1898, 363-382.

of the images observed. Apparently, however, the description is supplied in a later paper published in coöperation with Chwistek entitled "Ueber das periodische Verschwinden kleiner Punkte." At least a method of demonstrating changes in the curvature of the lens based on the behavior of the image reflected from its anterior surface is described here. But the validity of this demonstration is strongly open to question. In the experimental section of the present paper it will be shown that it is much more plausible to ascribe this behaviour to involuntary eye-movement than to involuntary changes in accommodation,—that in fact the same kind of behaviour has been described by de Schweinitz[23] and others, in case of the images reflected from the cornea, as one of the common phenomena of ophthalmometry due to eye-movement.

In the article entitled "Zur Erklärung der Intensitätsschwankungen eben merklicher optischer und akustischer Eindrücke,"[24] Heinrich discusses the effect of variation of intensity, or differences in intensity between the stimulus and its background on the fluctuation of visual stimuli. Marbe[25] had found that an increase of intensity increases the phase of visibility, and conversely a decrease of intensity decreases the phase of visibility.[26]

This, Heinrich thinks, is just what should be expected were the disappearances caused by recurring lapses in the adjustment of the lens. As will be shown in the next section of the present paper, however, these results offer no differential evidence in favor of the accommodation theory. They are just what would be expected in terms of any theory that has yet been advanced to explain the fluctuation of minimal visual stimuli. Heinrich also notes that for one of Marbe's observers the

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[23] G. E. de Schweinitz: *Diseases of the Eye*, Philadelphia and London, 1902, p. 739.

[24] *Op. cit.*, 366-369.

[25] Karl Marbe: Die Schwankungen der Gesichtsempfindungen, *Philosophische Studien*, VIII., 1893, 615-637.

[26] Marbe apparently was the first to make any separation of the phase of visibility from the phase of invisibility in drawing his conclusions, and even he did not take any account of the phase of invisibility in making his comparisons. The total times of visibility of his stimuli under the different conditions alone were compared. This tendency to break up the total period of fluctuation into its phases for purposes of comparison was a step in the right direction, but it was little heeded by his successors.

Marbe concludes that neither the fluctuation of the "Schrödersche Treppenfigur" nor the visual sensation is periodic. The phase of visibility of the visual stimulus increases with the increase in the difference in intensity between the stimulus and its background. The length of the period of fluctuation is a function of this increase.

phase of visibility was decreased when the image of the stimulus fell on the paraxial portions of the retina. This also, he says, is just what should be expected were the disappearance caused by changes in the curvature of the lens. So is it also what should be expected were adaptation the cause of the fluctuation, for one of the most conspicuous differences between the phenomena in the central and peripheral retina is the greater rapidity of adaptation in the peripheral retina.[27] Again, then, the evidence cannot be considered as differential. Heinrich also takes into consideration in this paper the results of Pace with the atropinized eye. He claims that changes in the curvature of the lens may still be observed when atropine has been used to paralyze the muscles of accommodation. While the present writer by no means contends that the muscles of accommodation are completely paralyzed by the use of atropine, still he would maintain that Heinrich's claim is strongly open to question if it is based on the kind of observation described by him and Chwistek in the article "Ueber das periodische Verschwinden kleiner Punkte." In any event the point is no longer of importance to the explanation of fluctuation, for it has been shown since that time by the present writer[28] that eyes from which the lenses have been removed and which under careful test shown no residual accommodation, get the fluctuation apparently just as readily as the normal eye.

In the article "Ueber das periodische Verschwinden kleiner Punkte," Heinrich and Chwistek, using stimuli of point area, attempt as their *experimentum crucis* to demonstrate the

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[27] In fact in the writer's own experiments, designed to show the correspondence between adaptation and fluctuation in the peripheral retina, the farther the stimulus was moved towards the periphery of the retina the shorter became the phases of visibility and the longer the phases of invisibility. These experiments were made differential for the adaptation theory (a) by the method of variation of areas, and (b) by showing a rough correspondence between the phase of visibility in the fluctuation experiments with the adaptation time for different visual stimuli from center to periphery of retina. No. 27 gray and the red, green, blue, and yellow of the Hering series of papers were used as stimuli. Only a partial list of the results obtained was published, however, because the writer did not at that time consider the phenomenon in indirect vision worthy of more space. The main arguments were established for direct vision and no more data were included for indirect vision that were needed to show in a general way that the phenomena here present no exception. (See "An Experimental Examination of the Phenomena Usually Attributed to Fluctuation of Attention," 116-119.)

[28] See An Experimental Examination of the Phenomena Usually Attributed to Fluctuation of Attention, 84 and 94-96.

coincidence of fluctuation and changes in accommodation. Heinrich had mentioned the desirability of making this demonstration in the preceding paper, but had discarded the idea as infeasible because of the conditions under which the experiment would have to be conducted. In choosing to work with point stimuli in this study, Heinrich and Chwistek have admittedly selected the conditions most favorable to the accommodation theory, for by Heinrich's own statement in the explanation of his theory in an earlier paper[29] changes in accommodation would be more apt to cause the disappearance of point stimuli than of stimuli of larger area. Notwithstanding this admission, however, the results they get with point stimuli are advanced in the later paper as evidence that the fluctuation of stimuli of all areas is due to involuntary changes in accommodation. Their work with stimuli of point area will be taken up in detail in the next section of this paper.

III. The Fluctuation of Stimuli of Point Area (the Work of Heinrich and Chwistek)[30]

Heinrich and Chwistek maintain that the fluctuation of visual stimuli of point area is caused by periodic changes in the curvature of the crystalline lens. They also offer their results for stimuli of point area as evidence that the fluctuations of stimuli of all areas are caused by changes in accommodation. Four arguments are advanced by them in support of this conclusion. (1) Periodic changes in the curvature of the lens are directly observable. Moreover, these changes are found roughly to coincide with the fluctuations of the point stimulus when both observations are conducted at the same time. They describe two methods of demonstrating this change of curvature. One may be considered popular, the other technical. The popular demonstration may be conducted as follows. Prick two holes in a cardboard nearer together than the breadth of the pupil of the eye. Hold the card close to the eye and look through the holes at a bright light. The holes will be seen as two dispersion circles with a bright overlapping area. When the curvature of the lens changes, the overlapping area alternately contracts and expands. That is, as the lens becomes more convex, the dispersion circles become smaller and the overlapping area becomes narrower; and conversely, as the lens becomes less convex the circles become

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[29] See Zur Erklärung der Intensitätsschwankungen eben merklicher optischer und akustischer Eindrücke, 366-67.

[30] W. Heinrich and F. Chwistek: *Zeitschr. f. Psychol.*, XLI., Abt. 2, 1907, 59-73.

larger and the overlapping area becomes broader. This change in the overlapping area, they say, can readily be observed. Their technical demonstration was accomplished by means of an ophthalmometer. Their method was as follows. Two spots of light were thrown on the eye of the observer by means of two mirrors reflecting the light from a lamp properly placed with reference to these mirrors and to the eye of the observer. These images were observed by means of an ophthalmometer. Their description of method is extremely meager. They say: "Lässt man die beobachtete Person den Punkt fixieren, dessen periodisches Verschwinden untersucht wird, und dreht die Glasplatten des Ophthalmometers, bis man in dem Instrument die beiden von der vorderen Linsenfläche reflektierten Bildchen als drei Punkte sieht, so offenbart sich jede Krümmungsänderung der Linse dadurch, dass der mittlere Punkt bei grösseren Änderungen sich spaltet, bei kleiner breiter wird. Man beobachtet dann ohne weiteres, dass die Linseneinstellung nicht stabil ist, sondern dass sie kleinen periodischen Aenderungen unterliegt. Diese Aenderung konnte mit unserem Instrument durch die Drehung der Platten um höchstens 0.5° kompensiert werden. Es war uns unmöglich die Aenderungsrichtung aus den Bewegungen des Punktes zu erkennen."[81] While these changes in the image reflected from the observer's eye were being recorded by a second person, the observer himself recorded the fluctuations of a point stimulus. Simultaneous records were thus obtained which could be compared in order to determine whether the phases of fluctuations coincided with the phases of changes in the image reflected from the eye. The point stimulus consisted of a small black point on a white ground or a small white point on a black ground, 0.1-0.3 mm. in diameter, observed at a distance of 70-150 cm. Two observers Herr Sk. and Herr Zacz, were used. The eyes of both were normal, or emmetropic. Chwistek recorded the changes in the images reflected from the eye. Their results are stated as follows. For observer Sk., 776 phases were recorded. "Einseitige Notierung vom Herrn Sk., d. h. notiertes Verschwinden des Punktes ohne entsprechend notierte Akkommodationsschwankung ergab sich in 38 Fällen. Einseitige Notierung vom Herrn Chwistek, d. h. notierte Akkommodationsänderung ohne entsprechende Aufzeichnung des Verschwindens des Punktes fand man in 40 Fällen." For observer Zacz, 296 phases were recorded. "Einseitige Notierung vom Herrn Zacz in 31 Fällen. Einseitige Notierung vom Herrn Chwistek in 32 Fällen."

[81] *Op cit.*, 60-61.

(2) Within the range of areas used by them an increase in the area of the stimulus was found to give longer phases of visibility and shorter phases of invisibility. And, conversely, a decrease in the area of the stimulus was found to give shorter phases of visibility and longer phases of invisibility. Points were observed ranging for one observer (emmetropic) from .2 mm.-.5 mm. in diameter, at distances ranging from 100 cm.-126.5 cm.; for another observer (2.5 myopic), .2 mm.-.5 mm. in diameter at distances ranging from 35 cm.-39 cm.; and for a third observer (4 D. myopic), .2-1.5 mm. at distances ranging from 15 cm.-28.5 cm.

(3) The phase of visibility was also found to vary with the intensity of the stimulus or with the brightness difference between the point and its surrounding field. The greater was this brightness difference, the longer the phase of visibility was found to be as compared with the phase of invisibility, and the less was this brightness difference, the shorter was the phase of invisibility.

(4) When the stimulus was placed just beyond the far point for an observer with myopic eye, it was found to become periodically more and less distinct. Also two points placed at this distance were found alternately to blur into one and to separate into two. Two observers were used in these experiments.

Before passing to his own experimental evidence that involuntary changes of accommodation are not an essential factor in the fluctuation of stimuli of point area, the writer has the following comments to make on the work of Heinrich and Chwistek. (1) In this work they have created for themselves a special problem, that is, they employed stimuli of point area and strongly supraliminal intensity. The fluctuation of such stimuli has never been ascribed to the fluctuation of attention. Historically considered, then, they are not working with the phenomenon to which they primarily make their conclusions apply; and, moreover, they have not in any way shown in a satisfactory manner the propriety of applying their conclusions to the phenomenon explained by Lange as due to the instability of attention. (2) Their popular demonstration of involuntary changes in the adjustment of the lens is strongly open to question. Employing 124 subjects, the writer has not been able to make it work in a single case in which care was taken to rule out extraneous factors which would themselves cause the phenomenon. For example, extreme care must be taken to hold the card steady. Any variation in the distance of the holes from the pupil of the eye will cause a

variation in the breadth of the overlapping area. Especially must care be taken that the card does not touch the lid of the eye, for movements of the ball of the eye and more particularly of the lid change the distance of the card from the eye. These movements are often unnoticed unless the observer is especially looking for them, and are frequently of sufficient range to cause a change in the size of the dispersion circles. Without a doubt the phenomenon, when it has occurred, has been, so far as the writer's experience is concerned, an artifact due to the conditions under which the observations were made. (3) Their technical demonstration by means of the ophthalmometer is, in the writer's opinion, just as strongly open to question. The writer criticizes this demonstration, however, with reluctance because of the meagerness with which they have described their method of working and observations. The following points, however, may be noted. (a) Working as they did, two images should have been observed, one reflected from the cornea, the other from the anterior surface of the lens.[32] Both images should have been very much alike, with the exception that the one reflected from the cornea should have been larger and more distinct. Nothing is said in the article, however, that would give evidence to the reader that more than one image was observed, or that the image described was actually reflected from the lens. But even if it were granted that the image observed was reflected from the lens, it would signify little, for the phenomenon described by them could have been caused just as well by involuntary eye-movements as by changes in the curvature of the lens. That is when the eye is accommodated, the anterior surface of the lens is hyperbolic in shape and varies in curvature considerably from point to point. A movement of the eye would, therefore, cause the rays of light forming the image to be reflected successively from points at which the surface had a different curvature. Each difference in curvature would give a difference in the size of the image reflected. Eye-movement would, therefore, produce the same effect in the size of the image as changes in the convexity of the lens. That is, movements of greater range would correspond in effect to the changes in convexity of greater magnitude, and, conversely, movements of lesser range to the changes in convexity of lesser magnitude. In fact, the phenomenon they describe is one of common

[32] An image reflected from the posterior surface of the lens might also have been observed. But since this image is inverted and is besides very indistinct, it may be considered as having no bearing on the discussion.

observation in case of the corneal image, and in this case no attempt has been made to ascribe it to recurrent changes in the curvature. For example, de Schweinitz, in his treatise on the diseases of the eye, says:[33] "Nothing is more common than to see the images of the mires [the mires correspond to the lights used by Heinrich and Chwistek] separate and overlap so that the apparent curvature of the cornea seems to change while under observation. The changes are due to slight movements of the eye which bring different portions of the cornea into view." We know that there are many involuntary eye-movements per minute even with the best control of fixation that can be obtained.[34] It seems more plausible, therefore, to attribute the phenomenon observed by Heinrich and Chwistek to the involuntary eye-movements which we know occur in abundance, than to use it as a proof of a new phenomenon, namely, the involuntary changes in the curvature of the lens, even if it be granted that the image from the lens was observed. At least, it may be said that Heinrich and Chwistek were not warranted in concluding as they did, without having secured any differential evidence to bear out their conclusion or without even having considered eye-movement as a causal factor. (d) Since the corneal image is known also to double and overlap, a rare opportunity was given to Heinrich and Chwistek, in making these observations, to compare the behaviour of the corneal image with that of the image reflected from the lens, if that really were the image they observed, and to determine by the presence or absence of coincidence in the two sets of changes, whether the doubling and overlapping of the images reflected from the lens has the same or a different cause from the doubling and overlapping of the images reflected from the cornea. Had both images really been observed or had the characteristic doubling and overlapping of the corneal image even been known to Heinrich and Chwistek, one can hardly conceive that their conclusions would have been drawn without recourse to this means of determining whether or not both sets of changes should be ascribed to a common cause. In short, judging from their report as it stands; from the fact that the ophthalmometer as it is ordinarily constructed and used is intended only for the observation of the corneal images, and that such a phenomenon as they describe would

[33] G. E. de Schweinitz: *Diseases of the Eye,* Philadelphia and London, 1902, 739.

[34] See C. E. Ferree: An Experimental Examination of the Phenomena Usually Attributed to Fluctuation of Attention, *Amer. Jour. Psychol.,* XVII., 1906, 113–115; also The Intermittence of Minimal Visual Sensations, *ibid.,* XIX., 1908, 83–112.

have been extremely difficult to observe in case of an image reflected from the lens; and from the fact that descriptions of similar behaviour on the part of the corneal image are given by other observers, the writer cannot help but think, without any wish to be hypercritical, that considerable grounds are given for suspecting that Heinrich and Chwistek have observed the doubling and overlapping of the corneal image which is commonly attributed by de Schweinitz and others to involuntary eye-movement.[35] Moreover, the crux of their argument is that they have actually observed a coincidence between the fluctuation of the visual stimulus and the changes in the adjustment of the lens. This, they contend, gives a certainty to their argument not yet attained in previous work on the problem. But even if the question whether or not it was a lens image that was observed be disregarded, it will be seen from the above discussion that is strongly probable that the coincidence they actually observed was between eye-movement and the fluctuation of the visual stimulus and not between changes in the curvature of the lens and the fluctuation of the visual stimulus.

(4) Their explanation of the effect of variation of area on the fluctuation of a visual stimulus could apply only to stimuli of very small area. Moreover, even in the case of very small areas the effect they got is just what might be expected as the result of increase of area either in terms of Loria's explanation of the fluctuation of stimuli of point area[36] or in terms of the writer's explanation: adaptation interfered with by eye-movement. They make two cases of their explanation of how changes of accommodation cause the fluctuation of stimuli of point area: (a) when the stimulus is a black point in a white ground and (b) when it is a white point in a black ground. In the former case the rays of light coming from the margin of the black point are not sharply imaged on the retina when the lens changes focus, hence they spread over the dark space on the retina corresponding to the black point. It is obvious that this spreading of the marginal light could blot out the dark space only in case the black stimulus were of very small area. Hence the explanation could not apply at all to stimuli of the size ordinarily used in the work on fluctuation. In the latter case the rays of light coming from the white point are not sharply imaged when the accommodation

[35] The writer leaves himself willingly open to correction on this point, however.

[36] See Heinrich and Chwistek: *op. cit.*, p. 60; also Stanislaw Loria: *Untersuchung über das periphere Sehen, Zeitschr. f. Psychol.*, XL., 1905, 160-186.

changes, and are spread over the surrounding dark space. Since strongly supraliminal stimuli were used, it is extremely doubtful whether even very small stimuli could be carried below the limen of sensation from this cause. Moreover, because strongly supraliminal stimuli were used and no attempt was made to control the intensity of the stimulus, an increase in the area of the stimulus would function for sensation as an increase of intensity.[37] Therefore, from this cause alone, according to the theories advanced either by Loria or by the writer, an increase of area would produce an increase in the phase of visibility. Even in case of stimuli of point area, then, the effect of increase of area described by Heinrich and Chwistek offers no differential argument in favor of the explanation advanced by them. Furthermore, the theory of fluctuation of attention was meant to apply only to stimuli of liminal or approximately liminal intensity. When such stimuli are used, an increase of area produces just the opposite effect. For example, working in 1906 with liminal stimuli ranging in area from .5 x .5 cm. to 15 x 15 cm., the writer found that an increase of area caused a decrease in the phase of visibility and a corresponding increase in the phase in invisibility. And in the experimental section of this paper it will be shown that the same effect is produced in case of liminal stimuli of very small area. In both of these cases care was taken to keep the stimuli liminal in order that an increase in the area of the stimulus would not produce an increase in the intensity of the sensation. (4) The fourth argument advanced by Heinrich and Chwistek has no differential value whatever. It was first used by Heinrich in 1898, as applied to stimuli of larger area.[38] A more intensive stimulus, he thinks, is not so liable to be blotted out by involuntary changes in accommodation. Therefore, he concludes, the more intensive is the stimulus the longer should be the phases of visibility and the shorter the phases of invisibility. It is obvious, however, that this result is just what should be expected from adaptation as a causal factor. It should be expected even were it held that fluctuation is due to instability of attention. In fact an increase in the phase of visibility and a decrease in the phase of invisibility would be the natural consequence of an increase in the

[37] We seem to have here a violation of one of the most fundamental principles in experimental procedure, namely, when it is wanted to determine the effect of a given factor, the effect of all other factors should, if possible, be eliminated from the results of the experiment.

[38] W. Heinrich: Zur Erklärung der Intensitätsschwankungen eben merklicher optischer und akustischer Eindrücke, *Bulletin International de l'Academie des Sciences de Cracovie,* Nov., 1898, 363-382.

intensity of the stimulus in terms of any theory that has yet been advanced to explain fluctuation.

(5) The writer is in some doubt as to what is meant by the fifth argument. "Befindet sich der Punkt, dessen Verschwinden man beobachtet, innerhalb des Akkommodationsbereiches der Linse, so beobachtet man nur das periodische Verschwinden desselben. Die Verhältnisse sind komplizierter, wenn man den Punkt ausserhalb des Fernpunktes aufstellt was beim myopischen Auge leicht ausführbar ist. In diesem Falle zeigt sich, dass der beobachtete Punkt, der jetzt nicht scharf gesehen wird, periodisch verschwindet, aber auch periodisch schärfer gesehen wird."[39] In the first place he cannot understand why the above result should be expected, were changes in accommodation present, for when the far point is actually reached the ciliary system should be completely relaxed. It is difficult then to see how the lens can be allowed to become any flatter, unless indeed it be held that the theory of accommodation commonly accepted for the human eye is incorrect. And in the second place, working under the conditions described by Heinrich and Chwistek, the writer has been unable to get anything that might be called three distinct and separate stages of clearness of his stimulus. Moreover, any stimulus of supraliminal intensity, fluctuating from any cause whatsoever and especially from causes purely retinal, would be apt to have, although not sharply defined, maximum, minimum, and intermediate degrees of distinctness. This the writer's observers were able to get at whatever distance the stimulus was put from the eye, but they were utterly unable to detect the three distinct and separate stages that are reported by Heinrich and Chwistek. Nor were they ever able to see the stimulus as clearly beyond the far point as they were at the far point or nearer than the far point. In short, there was never at this point what could be considered a norm of clearness which was succeeded either periodically or even at irregular intervals by a degree of clearness in excess of this norm. Continuing, Heinrich and Chwistek say: "Das lässt sich am besten durch folgendes Experiment illustrieren: Stellt man nicht weit ausserhalb des Fernpunktes des myopischen Auges als Objekt zwei Punkte, die so nahe liegen dass sie als ein Fleck gesehen werden, so beobachtet man, dass die Punkte periodisch auf kurze Zeiten getrennt erscheinen." The writer has not succeeded in getting this phenomenon when working beyond the far point with the myopic eye. It is, however, of common occurrence for any eye when the points are placed

[39] *Op. cit.*, 66.

at or slightly nearer than the limit of clear vision for these points and are regarded for any length of time. The points alternately blur into one and separate into two. In all probability both retinal and accommodation factors are involved in this result, but no definite estimate can be made of how much importance should be assigned to either until comparative records be made for subjects without lenses and for normal subjects. In the writer's opinion, however, the above experiment comes the nearest of any yet described by Heinrich and Chwistek to giving tangible evidence that involuntary changes in accommodation occur. But even to demonstrate clearly that these changes occur, would not prove that they are essential or even important factors in the fluctuation of minimal visual stimuli even of point area.[40] That they are not essential factors will be shown by the writer in the next section of this paper.

IV. Experimental

In this section of our paper we propose to show (1) that involuntary changes in accommodation are not essential or even important factors in the fluctuation of minimal visual stimuli of point area, and (2) that, identified by tests used by the writer in his earlier experiments, these fluctuations correspond just as closely to adaptation phenomena as they do for stimuli of larger area.

Probably the most convincing proof that one can offer that involuntary changes of accommodation are not essential to the fluctuation of stimuli of point area is the results obtained from aphakial subjects. Observations were made by the writer upon four aphakial subjects. They were all above sixty years of age, and three were above seventy. All of them had had the lenses removed from their eyes from 15-20 years before. Both the advanced age of the subjects and the long period that had elapsed since their lenses were removed favored the absence of any residual accommodation. To make sure of this point, however, they were each tested as follows. The subject's head was clamped in a head-rest and a card bearing letters of very fine print (3½ point type) was slid along a meter rod supported at the level of his eyes in the

[40] Lest it be thought that this experiment shows some coincidence between changes in accommodation and fluctuation, it may be pointed out that the cycle of changes experienced by the two points does not even include disappearance. The points merely blur into one and separate into two. That is, the only phenomenon cited by Heinrich and Chwistek that really gives any tangible evidence of involuntary changes in accommodation does not even occur in a series in which fluctuations are found.

median plane. The card was placed at his point of clearest vision as determined by the focus of his glasses and was moved both nearer and farther until just noticeable dimming took place. Every precaution was taken to secure accuracy. For one of the subjects the card could not be moved more than 2 mm. from the point of clearest vision without becoming less distinct. Very little more movement was required for any of the subjects. It may be safely said that all were practically without accommodation. Two of these observers were the same as were used by the writer in the earlier investigations made with stimuli of larger area. Opportunity was thus had to determine whether or not changes in accommodation play a more important rôle in the fluctuation of stimuli of point area than of stimuli of large area. So far as could be told from the records in both cases, they do not play a more important rôle. In cases of stimuli both of large and of very small area, the fluctuations occur for the aphakial subject with apparently no greater variation from the normal subject than is found from individual to individual with normal eyes.

Of the methods used in the former work to demonstrate that fluctuation is a phenomenon of the adaptation of the sense organ, only three were available for stimuli of point area. In the first of these the stimuli were made of different colors. Speaking of this method in the first paper[41] of the former series, the writer says, "Colors and grays were found to have an order of fluctuation times corresponding to their adaptation times. Four colors, red, green, blue, and yellow, gave very different fluctuation periods as compared with each other and with No. 27 Hering gray. The visibility times obtained were in the following order: red, green, blue, and yellow, the yellow being nearly four times as long as the red.

"The complete adaptation times for sheets of the same colors were found to have the same order of length and a rough correspondence as to ratio of length. Further, a striking fact came out with regard to the phases of invisibility. Since red, for example, has a shorter phase of visibility than green, one might naturally expect that its phase of invisibility would also be shorter than the phase of invisibility of green. The reverse, however, is true. Red has a longer invisibility than green, and this peculiarity is especially marked if one considers the proportionality between the phases, *i. e.*, the ratio invisibility: visibility. The same thing is true of the complementaries blue

[41] An Experimental Examination of the Phenomena Usually Attributed to Fluctuation of Attention, p. 86.

and yellow. Clearly, we cannot look for a central explanation of this peculiarity; but it seems just what we might expect of adaptation from the standpoint of the compensation theory. The recovery process for the red is the green process. The green process is longer and seemingly more tenacious than the red, as is shown by the adaptation experiments proper, and is further borne out by the longer duration of the green after-image. A similar relation obtains in the blue-yellow process." In the earlier work, the stimuli were gotten as follows. Squares of the color of the size that was wanted were pasted on a gray of the brightness of the color. The stimulus was rendered liminal by letting the light pass from the colored paper through a sheet of milk glass, matt on one side, placed at such a distance from the color as to render its intensity liminal. The intensity was easily regulated by slight changes in the distance of this glass from the colored paper. The light reflected from the colored papers could not be used, however, for stimuli of point area, because the milk glass mentioned above had to be used to reduce the intensity of the stimulus and it was impossible to get this glass thin enough to give noticeable color with stimuli of point area. Light was transmitted through color-filters instead. The stimulus was gotten as follows. A hole was pricked through a gray cardboard with a fine needle and covered with one or more layers of colored gelatin. In front of the card, in contact with it, was placed the sheet of milk glass, matt on one side. The hole was illuminated by a row of lights placed behind the cardboard, normal to its surface, at a distance sufficient to render the stimulus liminal. By this arrangement a just noticeable point of color was presented to the observer seated in front.

A stimulus given by reflected light has always yielded more differential results in former experiments with the method of colors than a stimulus by transmitted light. This is probably due to the fact that we were able to get from the former type of stimulus more color in proportion to the white light present, thus better bringing out the color differences in the liminal stimuli. The poorer method had to be used, however, because as stated above milk glass with one surface matt could not be obtained thin enough so that a point of colored paper pasted upon a background of equal brightness could be seen through it.[42]

[42] In case of the colored papers the liminal stimulus and surrounding field were of the same brightness, because the paper giving the stimulus was pasted on a gray of the brightness of the color. The only effect of the milk glass in front was to change the general scale of brightness of color and surrounding field. No brightness inequality was produced.

The registration of results was secured by means of a Ludwig-Baltzar kymograph, a telegraph key and an electromagnetic recorder, a Jaquet chronograph (set to seconds), and a lamp rheostat to cut down the current from the lighting circuit. All of this apparatus was screened from the observer by means of a sliding curtain. The work was done in a long room with the windows all at one end. Thus cross lights, unequal illumination of the background, etc., could be avoided. The illumination of the room was kept fairly constant by means of thin curtains covering the windows.[43] The observer sat with his back to a high window and his head in a head-rest fastened to the edge of a long table, along which the frame bearing the stimulation apparatus was moved as required. The time used throughout was 1 sec. The following results were obtained. As in the earlier work with stimuli of a larger area, red showed a shorter phase of visibility and a longer phase of invisibility than green; and blue, a shorter phase of visibility and a longer phase of invisibility than yellow. In spite of the poorer method we were required to use, the results obtained were almost as strongly marked as they were when the same method was used with stimuli of a larger area. These results have been verified at the time this work was done and since by a large number of observers practiced and unpracticed. The results of three observers chosen as typical will be reported here. Tables I-III have been compiled from these results.

TABLE I

Obs. C.—Fluctuation with stimuli of the four principal colors of point area showing that the phases of visibility and invisibility have the characteristic adaptation and recovery peculiarities of these colors just as they have with stimuli of larger area.

Stimulus	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Red	4.36	.79	1.68	.65	2.585	.385	6.04
Green	5.30	.93	1.13	.42	4.690	.213	6.43
Blue	7.75	1.12	1.41	.71	5.496	.181	9.16
Yellow	13.10	1.76	1.32	.59	9.925	.100	14.42

In the case of the stimulus by transmitted light, this result was not so effectively secured because of the greater difficulty of equating the point of light and the surrounding field.

[43] To keep the illumination constant presupposes a means of measurement. At the time the writer had at his command no means of measuring the illumination of a room by daylight. For a method of

TABLE II

Obs. G.

Stimulus	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Red	5.1	1.12	1.26	.54	4.047	.247	6.36
Green	7.43	1.54	1.14	.37	6.517	.153	8.57
Blue	10.9	1.59	1.46	.52	7.466	.133	12.36
Yellow	Did not fluctuate at all during period of observation.						

TABLE III

Obs. Ca.

Stimulus	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Red	1.82	.59	1.62	.32	1.123	.890	3.44
Green	2.82	.53	1.27	.36	2.243	.450	4.09
Blue	4.15	.55	1.70	.35	2.441	.409	5.85
Yellow	5.22	.86	1.52	.51	3.434	.291	6.74

In the second test strips of colored paper of the breadth of a point and 5 cm. in length were used.[44] They were pasted on a gray background of the brightness of the color in each case and were observed as liminal color on the matt surface of the milk glass placed in front. They were arranged first with their longer dimension in the vertical plane, then in the horizontal plane. The former arrangement favored a maximal disturbance of adaptation for observers having the greater range and frequency of eye-movement in the horizontal plane, and gave with these observers in the fluctuation experiments a corresponding increase in the phase of visibility and decrease in the phase of invisibility. Conversely, the latter arrangement favored a minimal disturbance of adaptation for these observers and gave a corresponding decrease in the phase of visibility and increase in the phase of invisibility.

doing this, see C. E. Ferree and Gertrude Rand: An Optics-Room and a Method of Standardizing Its Illumination, *Psychol., Rev.,* XIX., 1912, 364-373.

[44] In this test we were able to use colored paper because strips, although only of the breadth of a point, could be seen when 5 cm. long through the sheet of milk glass we used.

For each observer careful records were made of the frequency and range of movement and the total time the eyes were moving according to the methods described in the former papers.[45]

Speaking of this test in the first paper of the former series, the writer says, pp. 84-90, " A more direct experimental confirmation than was afforded by the method of variation of areas of this view that eye-movement interferes with the course of adaptation and is also the conditioning factor for the wide range of variability found in the phases of visibility and invisibility in the fluctuation experiments, is given by the following results. An examination of average frequency of eye-movement in the horizontal and vertical planes during fixation showed that three of our observers had a marked excess in both frequency and range in the horizontal, while the fourth had an excess of frequency in the vertical, but of range in the horizontal plane. This appeared to mean that for three observers, there was greater change of stimulation, and consequently greater relief for the adapted elements, in the horizontal than in the vertical direction; while the reverse was true, though probably to a lesser degree, for the fourth. To test this interpretation, stimuli longer than broad were used, *e. g.*, slips of paper 5 mm. x 40 mm. When these were placed with the longer dimension vertical, the shorter dimension would fall in the direction of greater unsteadiness of fixation for the three observers who had the excess of eye-movement in the horizontal plane. Consequently, a maximal interference with adaptation for these stimuli would be obtained, and one might expect an increase in the phase of visibility and a decrease in the phase of invisibility. On the other hand, if the longer dimension were placed in the horizontal and the shorter in the vertical plane, the minimal interference possible for these stimuli would be secured, and a decrease in the phase of visibility and an increase in the phase of invisibility should ensue. For the fourth observer with the stimulus arranged as described above, the reverse should be true, but probably not in so marked a degree, since his range was greater in the horizontal, which fact to a certain extent would counteract the effect of frequency. . . . . That these methods of arrangements of stimulus caused a marked change in the phases of visibility and invisibility for each

[45] See An Experimental Examination of the Phenomena Usually Attributed to Fluctuation of Attention, 113-115; and The Intermittence of Minimal Visual Sensation, 84-87.

observer will be seen by inspecting the Tables. Indeed the correspondence between the quantities: $\dfrac{\textit{Visibility} \div \textit{invisibility}}{\textit{visibility}^1 \div \textit{invisibility}^1}$, and $\dfrac{\textit{frequency}}{\textit{frequency}^1}$, is much closer than was anticipated."[46]

The results for the strips of point breadth are given in Tables IV-VI. For all the observers whose results are given in these tables, both the range and frequency of eye-movement were greater in the horizontal than in the vertical plane.

The third test was based upon the fact that the time required for a colored stimulus to adapt depends to some extent upon the surrounding field.

The question of what is meant by adaptation is logically raised here; among the followers of the Hering theory, it has come to mean, apparently, simultaneous induction, and Aall, reviewing the writer's first article,[47] assumes that that is what is meant by adaptation in that

TABLE IV

Obs. H.—Fluctuation with horizontal and vertical arrangement of the stimulus. Showing how arrangements that favor maximal and minimal interference with adaptation affect the phases of visibility and invisibility. Stimulus 3 mm. x 50 mm.

Stimulus	Arrangement	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Red....	Vertical....	2.95	.64	1.68	.31	1.756	.569	4.63
"	Horizontal..	1.08	.23	2.29	.40	.471	2.120	3.37
Green...	Vertical....	4.04	.72	1.45	.26	2.786	.358	5.49
"	Horizontal..	1.69	.38	1.76	.37	.960	1.041	3.45
Blue....	Vertical....	5.40	.86	2.03	.51	2.660	.376	7.43
"	Horizontal..	2.51	.49	3.10	.46	.806	1.235	5.61
Yellow..	Vertical....	6.99	.97	1.45	.29	4.82	.207	8.44
"	Horizontal..	3.55	.72	2.10	.56	1.928	1.690	5.65

[46] For a more complete understanding why arranging the shorter dimension of the stimulus in the direction of the greatest eye-movement causes relatively long phases of visibility and short phases of invisibility; and conversely arranging the longer dimension of the stimulus in the direction of greatest eye-movement causes relatively short phases of visibility and relatively long phases of invisibility, see The Intermittence of Minimal Visual Sensations, 112-129; and The Streaming Phenomenon, 484-494.

[47] *Zeitschr. f. Psychol.*, XLIII., *Abt.* 2, 1906, 456-457.

TABLE V

Obs. R.

Stimulus	Arrangement	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Red....	Vertical....	3.60	.75	1.46	.24	2.548	.405	5.06
"	Horizontal..	1.14	.28	3.40	.75	.335	2.982	4.54
Green...	Vertical....	4.30	.62	1.39	.19	3.093	.323	5.69
"	Horizontal..	2.42	.47	2.36	.37	1.025	.975	4.78
Blue....	Vertical....	4.93	1.08	1.68	.34	2.933	.340	6.61
"	Horizontal..	2.95	.54	4.53	.89	.651	1.535	7.48
Yellow..	Vertical....	6.61	1.23	1.46	.31	4.527	.220	8.07
"	Horizontal..	3.26	.79	2.75	.49	1.189	.843	6.01

TABLE VI

Obs. G.

Stimulus	Arrangement	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Hering gray No. 27	Vertical....	8.48	1.32	2.03	.39	4.177	.239	10.51
"	Horizontal..	3.14	.71	3.21	.56	.978	1.022	6.35
Red....	Vertical....	5.09	1.12	1.84	.29	2.766	.361	6.93
"	Horizontal..	1.65	.38	3.61	.78	.457	2.187	5.26
Green...	Vertical....	7.42	1.29	1.94	.41	3.824	.261	9.36
"	Horizontal..	2.52	.48	2.98	.48	.845	1.182	5.50
Blue....	Vertical....	8.99	1.47	2.84	.39	3.165	.315	11.83
"	Horizontal..	3.88	.84	5.99	.97	.647	1.542	9.87
Yellow..	Vertical....	11.49	1.97	1.90	.32	6.047	.165	13.39
"	Horizontal..	4.84	.97	3.86	.89	1.254	.797	8.70

article. The writer, however, by no means believes that the tendency of a color to lose its saturation on prolonged exposure to the eye or of all grays to become mid-gray is due entirely or even to any considerable extent to simultaneous induction. He grants an influence to the surrounding field when there is a surrounding field, and is at present making a quantitative study of that influence, but it is obvious that the influence of the surrounding field can have no part in the phenomenon called general adaptation, for in that case the whole retina is stimulated by the same kind of light. It can apply to local adapta-

tion alone and even in local adaptation it cannot be considered a factor of primary importance. In 1838-1840 the loss of saturation experienced by a color on prolonged exposure to the eye was explained by Fechner[48] as due to the exhaustion or fatigue of the retinal elements. This explanation was adopted by Helmholtz, and became a feature of the Young-Helmholtz theory. Hering,[49] however, following a suggestion made by Godart, 1776,[50] and elaborated by Plateau, 1833-1835,[51] chose rather to consider the retina compensating in function. A compensating retina, it is obvious, should not exhaust. Hering bore himself out in this general position by claiming that the eye is ordinarily exposed to stimulation by white light from 15-18 hours during the course of a day, and yet at the end of that time it has not noticeably lost in its sensitivity to white light.

Hering himself apparently has not based his claim on experimental evidence. At least he neither offers results of his own nor quotes from the work of others. His conclusion seems to be drawn wholly from general observation. He says (Ueber Ermüdung und Erholung des Sehorgans, *Arch. f. Ophthal.*, XXXVII., 1891, (3), p. 2): "Anderseits ist es eine bekannte Thatsache, dass wir des Abends nicht merklich schlechter sehen als des Morgens und dass dies auch dann noch der Fall ist, wenn dem Tage eine in hellen Raumen durchwachte Nacht und ein neuer schlafloser Morgen folgt. Also einerseits fortwährende Ermüdung und zwar eine so schnell—vor sich gehende, dass schon nach einer wenige Secunde währenden—Fixierung eines weissen Objects auf dunklem Grunde sich die Folgen der "Ermüdung" durch ein deutliches negatives Nachbild verrathen, und anderseits trotz solcher fortwährenden raschen Ermüdung keine merkliche Beeinträchtigung des Lebens selbst bei tagelanger Belichtung der Netzhaut." He contends (p. 1) that according to the theory of fatigue, advocated by Helmholtz and Fick, this should not be. During an exposure of several hours to white light, the eye never has a chance completely to recover, hence should become from beginning to end of the period progressively more fatigued.

This conclusion is not at all in agreement with experimental results obtained by C. F. Müller (Versuche über den Verlauf der Netzhautermüdung. Diss. inaug., Zürich, 1866), for example, who from the results of his tests of the loss of sensitivity of the eye to white light from morning to night, concludes: "Am Abende erscheint der Retina irgend ein Object nur in 0.49 derjenigen Helligkeit, in welcher es ihr am Morgen erschienen wäre." Moreover, he found that the shape of the curve of fatigue undergoes a very decided change during the course of the day. Aubert also disagrees with Hering. He says

[48] G. T. Fechner: *Pogg, Ann.*, XLIV., 1838, 221, 513; XLV., 1838, 227; L., 1840, 193, 427. The theory was conceived earlier by Scherffer (*Abhandlung von den zufälligen Farben*, Wein, 1765; also *Journal de Physique de Rozier*, XXVI., 175, 273), who explained the negative after-image by the conception that the retina is diminished in sensitivity by fatigue produced by previous stimulation.

[49] Ewald Hering: *Zur Theorie vom Lichtsinne*, 1874; *von Graefe's Archiv*, XXXVII., 1891, (3), 1, and 1892, XXXVIII., (2), 252.

[50] de Godart: *Journal de Physique de Rozier*, VIII., 1776, (1), 269.

[51] Plateau: *Ann. de Chimie et de Physique*, LIII., 1833, 386; LVII., 1835, 337; *Pogg. Ann.*, XXXII., 1834, 543. More fully in *Essai d'une théorie générale, etc. Mem. de l'Acad. de Belgique*, VIII., 1834.

(Moleschott's Untersuchungen, VIII., 1862, 251; see also Beiträge zur Physiologie der Netzhaut. *Abhandlungen der Schlesischen Gesellschaft,* Breslau, 1861, 39): "Es erscheint mir also aus obiger Bemerkung hervorzugehen, dass *im Laufe des Tages durch die Einwirkung des Lichtes die Empfindlichkeit unserer Retina fortwährend abnimmt,* so dass wir am Abende weniger empfindlich gegen Licht sind, als des Morgens." Moreover, without supporting evidence either from general observation or from experiments on color, in fact in complete disregard of this evidence, Hering, as he has done in many other cases in his work on the optics of color, has generalized with regard to the retina's response both to white light and to colored light from the results of observations with white light alone. For example, it is scarcely necessary to point out that the eye cannot be exposed from 15-18 hours to colored light without loss of sensitivity to color. Without dwelling further, however, on the evidence for and against a compensation theory, it will be sufficient for our purpose here to point out that if one were to hold to a compensation theory in the Hering sense, it would be necessary for him to seek some other explanation than exhaustion for the loss of sensitivity of the eye, apparent or real, to color or brightness. Hering apparently conceives that this happens only in case two surfaces of different quality are juxtaposed, and then all that takes place is that each is induced over the other and the qualitative difference between the two tends to disappear. There is, then, no real loss of sensitivity of the eye to either. Both become alike because by induction they are mixed to equality. The following objections may be offered to the explanation. (1) As stated before, it cannot apply to general adaptation. Yet it is well known that the eye loses its sensitivity to color when the whole retina is stimulated by that color, in fact more rapidly than when only a part is stimulated, except perhaps in case of certain combinations of color and surrounding field. (2) It can apply to local adaptation only in case the two fields juxtaposed both belong to the brightness series. For example, when the eye is exposed for some length of time to a white surface contiguous to a black or a light gray to a dark gray, the lighter surface is observed to darken and the darker to lighten. This might be explained by the mixture of the two qualities by induction. The evidence afforded by the observation, however, is not at all differential, for the phenomenon may be explained just as well by exhaustion. A different situation entirely is presented, however, when the two contiguous surfaces are colored. In this case there is very little in the phenomenon that could by the most favourable interpretation be construed as a mixture to an intermediate color quality. For example, when red and blue are stared at in juxtaposition, we should expect, in terms of Hering's explanation, both surfaces to become purple with no more loss of saturation than would be attendant upon distributing each color uniformly upon both surfaces. This, however, is not at all what takes place. The prominent effect is loss of saturation. The two surfaces tend to become alike for the most part only because both tend towards gray. The blue, it is true, does acquire a tinge of violet, but it does this as the result of adaptation even when red is not juxtaposed. It probably does become slightly more reddish by being alongside the red, but the evidence of induction is not great. The red, likewise, may be modified a little by being alongside the blue, but the effect is even less noticeable than it is for the blue. Similar results are gotten with

green and yellow. In case the colors juxtaposed are complementary colors, the results of induction should be towards a cancellation to gray. But again the tendency towards gray which is actually observed affords no differential evidence for this theory of induction, because the shift towards gray can be explained just as easily in terms of the exhaustion theory. And that induction can have little to do with the phenomenon may be shown by the facts (1) that the tendency would have been towards gray had the whole retina been stimulated by one of the colors alone, and (2) that so far as can be told, the process is hastened little, if any, by the juxtaposition of the two colors. In the Lichtsinne, 1878, pp. 36-37 Hering describes the experiment upon which he bases his explanation of adaptation in terms of simultaneous induction. His device for stimulating the eye consists of a white and black surface juxtaposed. No attempt is made to extend the experiment to color. Moreover, in drawing his conclusions, no heed whatever is given to what would happen were the whole retina stimulated by light of one quality. This is a truly remarkable instance of a broad generalization made from a slender basis of fact.

The writer, then, does not wish it to be understood that he explains the fluctuation of minimal visual stimuli in terms of simultaneous induction. He has called this fluctuation a phenomenon of the adaptation and recovery of the sense organ, meaning by adaptation here, as in the original article, the progressive loss of sensitivity of the eye to colored and to colorless light caused by prolonged exposure. Just what the factors are in adaptation, will be made the subject of a further paper. They vary under different circumstances. In case of local adaptation, simultaneous induction is one of the factors, and in certain especial cases it may exert considerable influence, as is recognized in the test described above; but to make it the sole cause of the adaptation of the eye to its stimulus seems to the writer, in the face of the experimental evidence, to be little short of absurd.

In the earlier experiments it was found that by keeping the surrounding field constant and varying the stimulus, or conversely, by keeping the stimulus constant and varying the surrounding field, a difference in the period of fluctuation was obtained, showing itself chiefly in the phase of visibility. The same thing held in the recognized adaptation experiments. The variations in the phases of visibility and invisibility that were produced in the one, were produced in the other; the only departure from precise correspondence being that the differences were more marked in case of the recognized adaptation experiments, as would be expected from the longer duration of the process. The old series of Hering papers was used both in these experiments and in the experiments with stimuli of point area because combinations more favorable to rapid adaptation could be found in this series. Some of the combinations most favorable were the vermilion of the series on the blue-green, and the vermilion upon Hering gray No. 27; and some of the most unfavorable combinations were dark

red on yellow, and dark blue on yellow. The combinations favoring rapid adaptation gave in the fluctuation experiments a short phase of visibility and a long phase of invisibility, and conversely, the combinations unfavorable to rapid adaptation gave long phases of visibility and short phases of invisibility. Although the writer had carefully determined in an earlier experiment with large areas which were the favorable and which the unfavorable combinations, still in order to make the correspondence between fluctuation and adaptation still more complete, in cases of stimuli of very small area both adaptation and fluctuation experiments were conducted in the present study. As was the case in the earlier experiments, the advantages of a stationary stimulus and surrounding field had to be sacrificed in these experiments, because the use of the milk glass to reduce the saturation of the stimulus, as was done when a stationary system was used, would also have reduced the saturation of the color in the surrounding field. This would not have been desirable for the purpose of the experiment. Accordingly, the Masson disc with the broken radius of point breadth was substituted for the stationary system. In case of the adaptation experiments, a point of color of full intensity was pasted upon the various backgrounds and observed at the proper distance. In conducting this adaptation series with stimuli of point area, we were not only getting the results needed for comparison in our fluctuation series, but by using stimuli of full intensity, we were applying our test under precisely the same conditions used by Heinrich in his fluctuation experiments. In both cases the effect of the favorable and unfavorable combinations was plainly marked in the results. For the results of these experiments see Tables VII-X.

TABLE VII

Obs. R.—Showing that combinations that influence adaptation time correspondingly influence fluctuation for stimuli of point area just as they do for stimuli of larger area. Fluctuation series, stimulus-ring 0.3 mm. broad and of liminal intensity.

Stimulus	Background	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Red....	Blue.......	4.258	.81	1.930	.83	2.220	.450	6.215
Red....	Orange.....	6.041	.98	1.327	.59	4.552	.219	7.368
Red....	Yellow-green	6.10	.91	.933	.32	6.538	.152	7.033
Yellow..	Red........	9.166	1.10	1.125	.26	8.147	.122	10.291

TABLE VIII

Obs. B.

Stimulus	Background	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Red....	Blue.......	3.30	.82	2.871	.88	1.149	.870	6.171
Red....	Orange.....	5.083	.94	2.416	.75	2.103	.475	7.499
Red....	Yellow-green	4.125	.59	1.540	.64	32.678	.373	5.665
Yellow..	Red........	6.230	.94	1.050	.32	5.933	.168	7.28

TABLE IX

Obs. R.—Showing that combinations that influence adaptation time correspondingly influence fluctuation for stimuli of point area just as they do for stimuli of larger area. Adaptation series, stimuli of point area and of full intensity.

Stimulus	Background	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Red...	Blue.......	13.0	1.09	2.577	.76	5.044	.198	15.577
Red...	Orange.....	11.323	.90	1.112	.58	10.182	.098	12.435
Red...	Yellow-green	11.032	.87	.781	.32	14.122	.070	11.813
Yellow.	Red........	200.	No	fluctu	ation.			

TABLE X

Obs. B.

Stimulus	Background	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Red...	Blue.......	5.761	.59	5.833	.654	.987	1.012	11.594
Red...	Orange.....	6.636	.98	4.723	.76	1.405	.711	11.359
Red...	Yellow-green	10.751	1.05	4.854	.97	2.215	.451	15.605
Yellow.	Red........	200.	No	fluctu	ation.			

V. Conclusion

In conclusion the following points may be reviewed. (1) The work offered by Heinrich and Chwistek in support of the accommodation theory for the fluctuation of stimuli of point area was done with stimuli of full intensity. In using stimuli of this intensity Heinrich and Chwistek have created for themselves a special problem. The doctrine of fluctuation of attention has never been applied to the fluctuation of stimuli

strongly supraliminal in intensity. (2) Their strongest and most direct argument for the accommodation theory is their claim of having directly demonstrated a coincidence between involuntary changes of accommodation and fluctuation. The validity of this claim, however, rests primarily upon whether or not they have given a valid demonstration of the involuntary changes in accommodation. Their demonstration of involuntary changes in accommodation is strongly open to question. Employing 124 observers, the writer has been unable in a single case to make their popular demonstration work when care was taken to rule out extraneous factors which would themselves cause the phenomenon. And their technical demonstration with the ophthalmometer is in terms of a phenomenon which is described by de Schweinitz and others as one of the common phenomena of ophthalmometry due to eye-movement. The coincidence, then, which they claim to have observed between the fluctuation of stimuli of point area and changes in the curvature of the lens, is in all probability a coincidence between eye-movement and fluctuation. (3) Moreover, none of the evidence they have offered as indirectly proving the accommodation theory can be considered in any sense differential. All of it can be explained just as easily either in terms of the writer's adaptation theory or in terms of Loria's theory for the fluctuation of stimuli of point area. Some of it can even be explained in terms of any theory that has yet been advanced to account for the fluctuation of minimal visual stimuli. (4) The fluctuation of stimuli of point area presents no especial case. For (a) involuntary changes in accommodation are not an essential factor in these fluctuations. They take place for aphakial subjects apparently just as readily as for subjects with normal eyes. And (b) identified by the tests used by the writer in his earlier work these fluctuations correspond just as closely to adaptation phenomena as do the fluctuations of stimuli of larger area. (5) The fluctuation of minimal visual stimuli whether of large or small area is a phenomenon of the adaptation and recovery of the sense organ. And by adaptation is meant the progressive loss of sensitivity to colored and colorless light caused by prolonged exposure of the eye to these lights. It is not simultaneous induction. Simultaneous induction can be considered only as a minor factor in the adaptation of the eye to its stimulus.

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THE PROBLEM OF LIGHTING IN ITS RELATION TO THE EFFICIENCY OF THE EYE[1]

UP to the present time the work on the problem of lighting has been confined almost entirely to the source of light. The goal of the lighting engineer has been to get the maximum output of light for a given expenditure of energy. Until recent years little attention has been given to the problem in its relation to the eye. It is the purpose of this paper to outline in a general way some of the more important features of this phase of the subject, and to give some of the results of work that is now being done on the problems that these features present.

Confronting the problem of the effect of lighting systems on the eye, it is obvious that the first step towards systematic work is to obtain some means of making a definite estimate of this effect. The prominent effects of bad lighting systems are loss of efficiency, temporary and progressive, and eye discomfort. Three classes of effect may, however, be investigated: (1) the effect on the general level or scale of efficiency for the fresh eye; (2) loss of efficiency as the result of a period of work; and (3) the tendency to produce discomfort. Of these three classes of effect the last two are obviously the more important, for the best lighting system is not the one that gives us the maximum acuity of vision for the momentary judgment or the highest

[1] This paper, with some changes, was read before the American Philosophical Society of Philadelphia, April 4, 1913.

level of efficiency for the fresh eye. It is rather the one that gives us the least loss of efficiency for a period of work, and the maximum of comfort.

In 1911 the American Medical Association appointed a committee to study the effect of different lighting systems on the eye. The writer was asked to share in the work of this committee. The problem presented to him was to furnish tests that would show the effect of different lighting systems on the eye, and more especially to devise, if possible, a test that would show loss of efficiency as a result of three or four hours of work under an unfavorable lighting system. In his work directed along these lines he has succeeded in getting methods of estimating effect which after eighteen months of trial seem sufficiently sensitive to differentiate between good and bad lighting systems with regard to these points. He has undertaken, therefore, to determine (1) the lighting conditions that give in general the highest level or scale of visual efficiency; (2) the conditions that give the least loss of efficiency for continued work; and (3) the conditions that cause the least discomfort. This plan of work, it is scarcely needful to remark, will involve a wide range of experimentation. The crux of the problem is, however, to secure reliable methods of estimating effect. Having these methods, the factors, whatever they may be, distribution, intensity, quality, position of the light relative to the eye, etc., can be varied one at a time and the effects be determined. From these effects it should not be difficult to ascertain what lighting conditions are best for the eye, and what is the relative importance of the factors that go to make up these conditions. Further, it should be possible on the practical side to test out and perfect a lighting system before it is put on the market; also to deter-

mine the best conditions of installation for a given lighting system; to investigate the effect of different kinds of type and paper on the eye; to study the effect of different kinds of desk lighting, etc. In short, it is obvious that the usefulness of such tests is limited along these lines only by their sensitivity.

A detailed description of the tests we are using has already appeared in print.[2] Time can not be given to them here. A brief report only of some of the results of the work in which they have been employed is possible in the time placed at my disposal.

In the study of the problems presented to us in this field it has been thought best to conduct the investigation at first along broad lines in order to determine in a general way the conditions that affect the efficiency and comfort of the eye. Later a more detailed examination will be made of the ways in which these conditions have been worked out in the various types of lighting systems in use at the present time. The following aspects of lighting sustain an important relation to the eye: the evenness of the illumination, the diffuseness of light, the angle at which the light falls on the object viewed, the evenness of surface brightness, intensity and quality. The first four of these aspects are very closely interrelated, and are apt to vary together in a concrete lighting situation, although not in a 1:1 ratio. For the purposes of this paper these aspects will be grouped together and referred to as the distribution of light and surface brightness in the field of vision, or still more generally as distribution. The ideal condition with regard to distribution is to have the field of vision uniformly illuminated with

[2] "Tests for the Efficiency of the Eye Under Different Systems of Illumination and a Preliminary Study of the Causes of Discomfort," *Transactions of the Illuminating Engineering Society*, 1913, VIII., pp. 40–60.

light well diffused and no extremes of surface brightness. When this condition is attained, the illumination of the retina will shade off more or less gradually from center to periphery, which gradation is necessary for accurate and comfortable fixation and accommodation.

The factors we have grouped under the heading distribution can be most conveniently discussed perhaps with reference to four types of lighting systems in common use to-day: illumination by daylight, direct lighting systems, indirect lighting systems and semi-direct systems. In the proper illumination of a room by daylight, we have been able thus far to get the best conditions of distribution. Before it reaches our windows or skylights daylight has been rendered widely diffuse by innumerable reflections; and the windows and skylights themselves, acting as sources, have a broad area and low intrinsic brilliancy, all of which features contribute towards giving the ideal condition of distribution stated above, namely, that the field of vision shall be uniformly illuminated with light well diffused and that there shall be no extremes of surface brightness. Of the systems of artificial lighting the best distribution effects, speaking in general terms, are given by the indirect systems. In this type of system the source is concealed from the eye and the light is thrown against the ceiling or some other diffusely reflecting surface, in such a way that it suffers one or more reflections before it reaches the eye. In some of the respects most important to the eye, this system gives the best approximation of the distribution effects characteristic of daylight of any that has yet been devised. The direct lighting systems are designed to send the light directly to the plane of work. There is in general in the use of these systems a tendency to concentrate the light on the work-

ing plane or object viewed rather than to diffuse it, and, therefore, a tendency to emphasize brightness extremes rather than to level them down. Too often, too, the eye is not properly shielded from the light source and frequently no attempt at all is made to do this. The semi-indirect systems are intended to represent a compromise between the direct and indirect systems. A part of the light is transmitted directly to the eye through the translucent reflector placed beneath the source of light, and a part is reflected to the ceiling. Thus, depending upon the density of the reflector, this type of system may vary between the totally direct and the totally indirect as extremes and share in the relative merits and demerits of each in proportion to its place in the scale. By giving better distribution this type of system is supposed also to be a concession to the welfare of the eye, but our tests show that the concession, at least for the type of reflector we have used,[3] is not so great as it is supposed to be. In fact, installed at the intensity of illumination ordinarily used or at an intensity great enough for all kinds of work, little advantage is gained for the eye in this type of lighting with reflectors of low or medium densities; for with these intensities of light and densities of reflector, the brightness of the source has not been sufficiently reduced to give much relief to the suffering eye.[4] Until this is done in home, office and

[3] The reflectors we used were supplied to us by a prominent lighting corporation, interested neither in the manufacture nor the sale of lighting fixtures, in response to a request for a representative semi-indirect lighting system. Obviously, however, final conclusions should be reserved until the tests are extended to other types of reflectors.

[4] The semi-indirect system used by us was but little better for the eye than the direct system. The direct system we employed was the one in general use throughout the building in which our tests were made. It was installed about six years

public lighting we can not hope to get rid of eye-strain with its complex train of physical and mental disturbances.

It is not our purpose, however, at this time to attempt a final rating of the merits of lighting systems. For that our work is still too young. Moreover, there are relatively good and bad systems of each type, and good and bad installations may be made of any system. What we hope to do is by making an appropriate selection and variation of condi-

ago and is, therefore, not of the most modern type. It seems to the writer safe to say, however, that it gives effects fully as good as most direct lighting in actual use in the country to-day. Furthermore, it is difficult to believe that any great injustice has been done to direct lighting, so far as this principle of lighting has been commercialized up to this time, by the selection of this system, because of the fact that very little less loss of efficiency was obtained from the semi-indirect lighting system, which on account of its similarity to indirect lighting represents, we have good reason to believe from our results, a greater modification of direct lighting for the welfare of the eye than any that is found within the class of direct systems. However, a final conclusion will be reserved until a more extensive investigation of the direct systems has been made. The writer further does not wish to be understood as contending that direct lighting can not be accomplished in a way that is not excessively damaging to the eye. Doubtless great improvement can be made in this type of lighting if proper attention is given to the fundamental principles governing the effect of light on the eye. It does not seem to the writer, however, that the principle of direct lighting offers as great possibilities in this direction as the indirect; still he permits this also to remain an open question in his mind. It is obvious that much can be accomplished for the welfare of the eye in cases both of the direct and semi-indirect systems by using sources of large area and of low intrinsic brilliancy, by removing them as much as possible from the field of vision, by employing better means of diffusing the light, etc.

tions to find out what the factors are that are of importance to the eye, and from this knowledge as a starting point to work towards reconstruction.

With regard to the effect of the distribution of light and surface lightness on the eye a brief statement will be given here only of its effect on efficiency; and in the consideration of efficiency loss of efficiency will receive the major part of our attention. No attempt will be made, for example, to present the results of the study of the factors producing discomfort. The study of these factors has constituted for us an entirely separate and independent piece of work investigated by separate and independent methods.

Our tests for loss of efficiency[5] show that when the intensity and quality of the light

[5] The tests were made in a room 30.5 feet long, 22.3 feet wide, and 9 feet high. The artificial lighting was accomplished by means of two rows of fixtures of four fixtures each. Each row was 6 feet from the side wall and the fixtures were 6 feet apart. The reflectors were in the different cases 19–26 inches from the ceiling. Clear tungsten lamps were used as source. The voltage was kept constant by means of a voltmeter and a finely graduated wall rheostat placed in series with the lighting circuit. In case of the direct system two bulbs making an angle of 180° were used for each fixture and the distribution was obtained by means of white slightly concaved porcelain reflectors 16 inches in diameter fastened directly above. In case of the indirect system corrugated mirror reflectors, enclosed in brass bowls, were used. For the semi-indirect system the distribution was obtained by means of inverted alba reflectors 11 inches in diameter which threw a part of the light against the ceiling and transmitted the rest directly to the room, minus a rather large absorption quantity. The daylight illumination came from three windows all on one side of the room and situated in a line parallel with the line of sight used when making the tests. These windows were so sheltered that it was never possible for them to receive light directly from the sun or from a brightly illuminated sky. Moreover, the

are equalized at the point of work, the eye loses practically nothing in efficiency as the result of three to four hours of work under daylight. It loses enormously for the same period of work under the system of direct lighting selected for our work and almost as much under the system of semi-indirect lighting. Under the system of indirect lighting, however, the eye loses but little more than it loses in daylight. The results of these tests show also that acuity of vision as determined by the momentary judgment is

light from one of them, the one nearest the observer, was further diffused by passing through a diffusion sash made of double thick glass ground on one side. The intensity in foot-candles was made equal at the point of work for all the systems employed. In making this equalization the light was photometered in five directions at the point of work: with the receiving surface of the photometer in the horizontal plane, at angles of 45° and 90° pointing towards the observer, and at angles of 45° and 90° pointing in the opposite direction. In installing the lights in the different systems it was impossible to make the intensity equal in all of these directions. Care was taken to make it equal in the plane of the test card, *i. e.*, the vertical plane, and as nearly as possible equal in the other planes. The Sharpe-Millar portable photometer was used to make these measurements, also another method mentioned in a former paper (*op. cit.*, p. 49) which is more sensitive to daylight illumination than is the Sharpe-Millar method. The effect of varying distribution of light was thus tested under conditions in which quality and intensity were reduced as nearly to a constant as was possible with the systems employed. The intensity in the vertical plane was made in each case 1.4 foot-candles or approximately so. Space can not be taken here for an engineering specification of the installations used and the lighting effects produced. A full report of the work including detailed brightness and illumination measurements, photographs showing the illumination effects obtained, descriptions of installations, etc., will be published in the *Transactions* of the Illuminating Engineering Society.

higher for the same foot-candles of illumination for the daylight system than for the systems of artificial lighting, and that for the latter systems, it is highest for the indirect system, next highest for the semi-indirect system, and lowest for the direct. It will thus be seen that for all purposes of clear seeing, whether the criterion be maximum acuity or the ability of the eye to hold its efficiency for a period of work, the best results are given in order by the systems that give the best distribution of light and surface brightness. The effect of distribution is not so great, however, on the ability of the fresh eye to see clearly as it is on its power to hold its efficiency.

The loss of efficiency found in the above work seems to be predominantly, if not entirely muscular, for the tests for the sensitivity of the retina show practically no loss of sensitivity as the result of work under any of the lighting systems employed. The following reasons are suggested why the muscles of the eye giving both fixation and accommodation should have been subjected to a greater strain by the systems of direct or semi-direct lighting, than by the system of indirect lighting or daylight. (1) The bright images of the sources falling on the peripheral retina which is in a perpetual state of darkness-adaptation, as compared with the central retina, and is, therefore, extremely sensitive in its reaction to such intensive stimuli, set up a reflex tendency for the eye to fixate them instead of, for example, the letters which the observer is required to read. (2) Likewise, a strong reflex tendency to accommodate for these brilliant sources of light, all at different distances from each other and the lettered page, is set up. (3) These brilliant images falling on a part of the retina that is not adapted to them, causing as they do acute discomfort in a very short period of time, doubtless induce spasmodic contractions of the muscles which both disturb the clearness of

vision and greatly accentuate the fatiguing of the muscles. The net result of all these causes is excessive strain, which shows itself in a loss of power to do work. In the illumination of a room by daylight, however, with a proper distribution of windows, the situation is quite different. The field of vision contains no bright sources of light to disturb fixation and accommodation and to cause spasmodic muscular disturbances due to the action of the intensive light sources on the dark-adapted and sensitive peripheral retina. As has already been pointed out, the light waves have suffered innumerable reflections and the light has become diffuse. The field of vision is comparatively speaking uniformly illuminated and there are no extremes of surface brightness. The illumination of the retina, therefore, falls off more or less gradually from center to periphery, as it should to permit of fixation and accommodation for a given object with a minimum amount of strain.

It is not our purpose, however, to contend that distribution is the only factor of importance in the illumination of a room. We have chosen to begin our work with types based on distribution, only because it has seemed to us, both from our own work and from a survey of the work done by others, that this is the most important factor with which we have yet to deal in our search for the conditions that give minimum loss of efficiency and maximum comfort in seeing. The quality of light and its intensity at the source are already pretty well taken care of, apparently better taken care of, at least in general practise relative to their importance to the eye, than is distribution. A systematic study of factors, however, can not stop with an investigation of the effect of distribution alone. The intensity and quality of light must also be taken into account. For example, one of the most persistent questions asked by the illuminating engineer is, "How much light should be used with a given

lighting system to give the best results for seeing?" We have undertaken, therefore, to determine the most favorable range of intensity for the four types of distribution mentioned above. Curves have been obtained showing the effect on the efficiency of the eye of three or four hours of work under different intensities of light, for the direct and semi-indirect systems; and rough comparisons have been made for the indirect system and for daylight. Detailed tests will be made for these latter two systems early next year. Our tests show, in general, the following results. A very wide range of intensity is permissible for daylight and the indirect system. For the semi-indirect system the eye falls off heavily in efficiency for all intensities with the exception of a narrow range on either side of 2.2 foot-candles, measured at the level of the eye at the point of work with the receiving surface of the photometer in the horizontal plane. For the direct system no intensity can be found for which the eye does not lose a very great deal in efficiency as the result of work. Thus it seems that distribution is fundamental. That is, if the light is well distributed and there are no extremes of surface brightness as is the case for daylight and the indirect systems of artificial lighting, the ability of the eye to hold its efficiency is, within limits, independent of intensity. In short, the retina is itself highly accommodative or adaptive to intensity, and if the proper distribution effects are obtained, the conditions are not present which cause strain and consequent loss of efficiency in the adjustment of the eye.

Details of the conditions of installation and of the methods of working can not be given here. It will be sufficient to state that the work was done in the same room, with the same fixtures, and in general with the same conditions of installation and methods of working as were used in the tests for distri-

bution. Nor can a full statement of results be made. Time will be taken, however, for a more detailed examination of the results obtained for the direct and semi-indirect systems. For the semi-indirect systems, our test showed that the intensity most favorable to the eye was secured when the photometric reading with the receiving surface in the horizontal plane showed 2.2 foot-candles of light at the point of work, 1.52 foot-candles in the 45° position, and .58 foot-candle in the vertical position. At this intensity of illumination, the semi-indirect system, so far as its effect on the eye's loss of efficiency is concerned, compares fairly well with the indirect system at such ranges of intensity as we have employed. At intensities appreciably higher than this most favorable value, or lower, the loss of efficiency is very great. At the intensity commonly recommended in lighting practise, the semi-indirect system is almost, if not quite, as damaging to the eye as the direct system. The intensity recommended by the Illuminating Engineering Society, for example, in its primer issued in 1912, ranges from 2–3 to 7–10 foot-candles, depending upon the kind of work. Five foot-candles is taken as a medium value. This medium value, it will be noted, is more than double the amount we have found to give the least loss of efficiency for the type and installation of semi-indirect system we have used. The intensity we have found to give the least loss of efficiency for this type of lighting, does not, however, give a maximum acuity of vision as determined by the momentary judgment. At an intensity that does give maximal acuity for the momentary judgment the eye runs down rapidly in efficiency. That is, in this type of lighting, one or the other of these features must be sacrificed. High acuity and little loss of efficiency can not be had at the same intensity. They could both be had only under the indirect system and daylight. How-

ever, the amount of light we find to give the least loss of efficiency seems to be sufficient for much of the work ordinarily done in the home or office. It is not enough, though, for drafting or work requiring great clearness of detail.

In case of the direct system, we were able to improve the conditions, so far as loss of efficiency is concerned, by reducing the intensity; but the system never proved so favorable in this regard as even the semi-indirect system. In the tests made under the direct system care was taken to have the fixtures in the same position in the room in every case as they were for the semi-indirect system. The most favorable intensity is secured by an installation that gave 1.16 foot-candles in the horizontal, .85 in the 45° position and .45 in the vertical. At this intensity, however, the loss in the efficiency of the eye for three hours of work was almost four and one half times as great as for a wide range of intensities for either the indirect system or daylight.

Two facts, then, may be emphasized at this point. (1) Of the lighting factors that influence the welfare of the eye, those we have grouped under the heading distribution apparently are fundamental. They seem to be the most important we have yet to deal with in our search for the conditions that give us the minimum loss of efficiency and the maximum comfort in seeing. If, for example, the light is well distributed in the field of vision and there are no extremes of surface brightness, our tests seem to indicate that the eye, so far as the problem of lighting is concerned, is when the proper distribution is present, intensities high enough to give the maximum discrimination of detail may be employed without causing appreciable damage or discomfort to the eye. (2) For the kind of distribution effects given by the majority of lighting systems in use at the present time, our results

show that too much light is being employed for the welfare and comfort of the eye.

The effect of quality of light on the eye has been the subject of much discussion and much misunderstanding. There seems to be a feeling even among lighting engineers and ophthalmologists that colored light gives better results for seeing than white light. Some, for example, hold that the kerosene flame furnishes the ideal source of light and that its virtues are due largely to the yellow quality of the light it gives off. While the writer has not as yet begun a systematic study of the effect of quality of light, and while he is, therefore, not as yet willing to commit himself on this point, he will say that when intensity and distribution are equalized, an installation of clear carbon lamps, which gives a light comparatively rich in yellow and red, causes the eye to fall off more in efficiency as the result of 3–4 hours of work than an installation of clear tungsten lamps, the light from which is more nearly white. In short, the question whether or not white or colored light is better for the eye can not be answered until definite tests are made of this point alone under conditions in which all other factors are rendered constant. The effects of the kerosene flame, for example, as compared with other sources of illumination, must be tested under a system of installation that gives the same intensity at the source, and, as nearly as possible, the same distribution in the field of vision as is given by other illuminants. This has not been done at all. Our judgment of the comparative merits of the color quality of the light given by it have been based on the roughest kinds of impression, obtained under conditions of installation in which there has been no attempt at control of the other factors that influence the effect of light on the eye. The work that has been done up to this time on the relation of quality of light to seeing has been confined to visual acuity as determined by the

momentary judgment, and even this work which alone can give no safe grounds at all for drawing general conclusions as to the effect of light on the welfare of the eye, shows, whenever the comparison has been made, that white light gives a greater acuity of seeing than light with a dominant color tone. If, as has been maintained by some on the grounds of their working experience, the kerosene flame is easier on the eye than the more modern sources of illumination, the writer would be inclined, more especially in view of his results on the effect of differences in intensity on the efficiency of the eye, to ascribe the benefit, whatever there may be, to the low intrinsic brilliancy of the kerosene flame. For, as has already been stated, it may be safely said that for the kind of distribution effects we are getting from the large majority of our lighting systems, too much light is being used for the welfare and comfort of the eye. Added to this is the effect of the position of the light in the field of vision. The kerosene lamp may be placed at the back or side of the person using it, and, if in the field of vision, it is usually at or near the level of the eye. In the two former cases the effect of concealed lighting is given, and in the latter case the lamp occupies the most favorable position possible for an exposed source. That is, if the source of light is to be in the field of vision at all, it should be as nearly as possible at the level of the eye. This is because of the greater tendency of a light source to produce discomfort and loss of efficiency when its image falls on the upper and lower halves of the retina than when it falls in the horizontal meridian. These facts have been clearly brought out in our work on the effect of position of the light in the field of vision.

In addition to studying the conditions that give us maximum efficiency, it is important to determine the lighting conditions and eye factors that cause discomfort. In fact, it

might well be said that our problem in lighting at present is not so much how to see better as it is how to see with more comfort and with less damage to the general health on account of eye-strain. Any comparative study of the conditions producing discomfort necessitates a method of estimating discomfort. As stated earlier in the paper, our method of estimating discomfort is entirely distinct and separate from our method of studying efficiency. Time can not be taken here to go into details of either the method or of the results of this study. It will be sufficient to say that the effect of distribution of light and surface brightness, intensity, and quality are also being studied in their relation in the comfort as well as to the efficiency of the eye.

In conclusion, the writer wishes to point out that no one of the factors he has mentioned can be safely omitted in the search for the most favorable conditions of lighting. Nor can one be investigated and a correlation between it and the others be taken for granted. We have been content, heretofore, to base our conclusions with regard to the relation of a lighting system to seeing on the conventional visual acuity test. While this test may tell us something about the general level or scale of efficiency of the fresh eye, it can tell us nothing of loss of efficiency, because the muscles of the eye, although they may have fallen off enormously in efficiency, can under the spur of the will be whipped up to their normal power long enough to make the judgment required by the test. Moreover, it tells us nothing of the conditions that produce discomfort. In short, the general level or scale of efficiency of the fresh eye, loss of efficiency as the result of work, and the tendency to produce discomfort constitute three separably determinable moments, no one of which should be neglected in installing a lighting system.

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A PRELIMINARY STUDY OF THE DEFICIENCIES OF THE METHOD OF FLICKER FOR THE PHOTOMETRY OF LIGHTS OF DIFFERENT COLOR

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A PRELIMINARY STUDY OF THE DEFICIENCIES OF THE METHOD OF FLICKER FOR THE PHOTOMETRY OF LIGHTS OF DIFFERENT COLOR[1]

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Synopsis

A satisfactory method of photometry should combine the following features. (1) It should enable one to detect small differences in luminosity and to reproduce results for a given observer with a small mean variation and for a number of observers with a comparatively small mean variation. That is, the method should possess an adequate degree of sensitivity. (2) It should be known either to possess of itself logical sureness of principle or its results must agree in the average with those of some method which can be shown to have this sureness of principle. The method of flicker probably satisfies the first of these requirements better than the equality of brightness method. It does not, however, possess of itself the needed sureness of principle, nor have its results been shown to agree in the average with any method which is accorded sureness of principle. Points are enumerated in the paper appended which raise doubt with regard to the correctness of the photometric balance obtained by the method of flicker. Only one of these is discussed, namely, the influence of the time element in the exposure of the eye to the lights to be compared. With regard to this point, it is shown from experimental data (1) that the sensations aroused by lights differing in color value rise to their maximum brightness at different rates; and (2) that the single exposures used in the method of flicker are much shorter than is required for these sensations to rise to their full value. The eye, therefore, is very much underexposed to its stimulus by the method of flicker. That is, the rate of succession used in the method of flicker is too fast for the single impressions to arouse their maximum effect in sensation and too slow for the successive impressions to add or summate as much as they would need to do to rise to their full value or perhaps even to a higher value than would be given by the individual exposures. Only one other possibility for a correct balance remains,—equality is attained at some value lower than the full value. This can not be assumed, however, without violating well-known laws relating to the factors which influence persistence of vision.

The principal point of discussion, then, is to what degree it should be held that the difference in lag between the sensations aroused by the single exposures used in the method of flicker is obliterated in a succession of exposures. Broadly considered, three positions are possible with regard to the point for the rates of succession that are employed in the method of flicker. (1) The difference is not obliterated at all. In this case the photometric balance should deviate from the true balance in direct pro-

[1] Paper read by C. E. Ferree at the Philadelphia section of the Illuminating Engineering Society, January 16, 1914.

portion to the difference in lag for the single exposures. (2) The difference is in part obliterated, but it is still present to a degree which renders the method untenable for precise work. And (3) the difference is entirely obliterated or so nearly so as to be of no practical consequence to the validity of the method. The second is approximately the position taken in this paper. The following evidence is offered in support of this position. (*a*) At high intensities of light the writers get by the method of flicker a deviation from the true photometric balance, as determined by the equality of brightness method, in a direction which corresponds to the difference in lag between these colors at high intensities as determined both in their own laboratory[1] and by Broca and Sulzer. (*b*) At low intensities they get a difference in lag for the colors which is in the same direction as the deviation obtained by Ives and Luckiesh at low intensities (the reverse Purkinje effect). (*c*) A change in the relative lengths of exposure to the two lights in the method of flicker produces a deviation from the equality of brightness balance which again corresponds in direction to the changes that are produced in the sensations aroused by the single exposures when similar changes are made in the relative lengths of exposure. And (*d*) determinations made at several intensities of light by the method of flicker show a deviation from the equality of brightness balance which is many times the smallest difference in brightness that can be detected by the method. Moreover, in their own results the writers find that these deviations in every case correspond to the difference in lag given by lights of the same order of magnitude of intensity, so far as can be judged from the determinations of lag that have been made up to this time. When, however, determinations have been made on a larger number of observers, individual differences may be found in the amount and distribution of lag just as they have been found in the amount and direction of the deviation of the flicker from the equality of brightness balance. Later in the interests of a fairer comparison the writers hope to make in every case compared the determination of lag and the photometric determinations on the same observer.

The writers have preferred to call the work of which this paper is a brief report a preliminary study for the following reasons. (1) Only one of the points directly pertaining to the method of flicker that should be investigated has been taken account of in the work. And (2) to complete the chain of evidence needed for this point, a more especially directed and perhaps more careful determination should be made than has yet been done of the time required for visual sensations colored and colorless to rise to their maximum of intensity. Such a study with especial reference to the needs of photometry is now in progress in our laboratory, but is as yet unfinished.[2]

[1] See this paper, footnote 1, pp. 125–130.

[2] In the work now in progress in our laboratory, attention will be paid to the following points. In case of colors, care will be taken to use lights of a small range of wave-length. The intensities of the lights used will be specified photometrically and radiometrically. The white light will in addition be specified either spectro-photometrically or spectro-radiometrically. For the sake of the comparisons needed in

A satisfactory method of photometry should combine the following features. (1) It should enable us to detect small differences in luminosity and to reproduce our results for a given observer with a small mean variation and for a number of observers with a comparatively small mean variation. That is, the method should possess an adequate degree of sensitivity. (2) It should be known either to possess of itself logical sureness of principle, or its results must in the average agree with those of some method which can be shown to possess this sureness of principle. Methods having these features have been developed for the photometry of colorless light. The problem of the photometry of colored light, however, has presented great difficulty.

Methods of Photometering Colored Light.

The methods for photometering colored light may be grouped under two headings: the direct methods and the indirect methods. In the former class we have the method of direct comparison or, as it is sometimes called, the equality of brightness method. Of the latter class the method of flicker has received the greatest amount of attention and has been the most favored. It will be the purpose of this paper (1) briefly to compare the relative advantages and disadvantages of the method of flicker and the equality of brightness method with regard to sensitivity; (2) to show that the method of flicker, so far as it has been developed up to the present time, does not seem to possess of itself the sureness of principle needed to meet the requirements of a satisfactory method; and (3) to show that as yet its results have not been found satisfactorily to agree in the average with those of any method which can be shown to have this sureness of principle. In a

the photometric work, all determinations for lights differing in composition will be made at the different intensities employed with stimuli equalized photometrically. Comparative results will be obtained for the same observers for the best of the methods already in use, and three new methods will be introduced. In part, results will be obtained for observers who have also been employed in the work on the method of flicker. The work will be done for different intensities of light, and both under dark and light room conditions. In a survey of the work done up to the present time, one can not help but note that too little care has been taken to observe even some of the most essential of the above conditions.

later paper a new method of photometry will be described which possesses approximately as high a degree of sensitivity for color work as the method of flicker and gives results which agree much more closely in the average with those obtained by the equality of brightness method. The second of the above points will be shown as follows. It will be pointed out that at the rate of speed at which the impressions are given in the method of flicker, the eye is very much underexposed to its stimulus. It can reasonably be assumed that this underexposure causes a reduction of the intensity of the sensation, and should lead, therefore, to a false estimation of the brightness of the colors. In fact, at the rate of rotation of the exposure apparatus required for lights of the order of intensity employed in practical work, this reduction produces for the observers we have used an effect similar to the Purkinje phenomenon.[1] At least a deviation from the equality of brightness values is found in our results for such intensities which accords well with the Purkinje phenomenon. That is, reds and yellows are underestimated in brightness, and blues and greens are overestimated. And (*b*) it will be shown that flicker itself, the phenomenon on which the equalization at the photometric screen is based, is subject to variations depending upon a number of factors the effect of which has not in all cases been adequately studied and in some cases not even recognized. An investigation of one of these alone, the effect of varying

[1] We do not mean to draw too close an analogy here between the effect on the brightness of sensation produced by keeping the intensity of light constant and reducing the time of exposure of the eye to the light, and the effect produced by keeping the time of exposure of the eye constant and reducing the intensity of the light employed (the Purkinje phenomenon). In attempting to interpret the effect produced by the short exposures used in the method of flicker, our data should be taken primarily from the results showing the relative rise of sensation to its maximum for white light and lights of the different colors. (See discussion of the development time of sensation, pp. 118–130). It is quite possible and in fact quite probable from Broca and Sulzer's results, for example, that for a part of the upward course blue and green rise faster than red, and conversely for a part of the course red rises faster than blue and green. (Yellow was not used by Broca and Sulzer.) The results of Broca and Sulzer are cited on this point, not by any means because their method of making the determination is the freest from criticism of any that have yet been used, but because they alone have attempted to plot the comparative curves for the different colors and white light at different points from the threshold to the maximum.

the ratio of the time of exposure of the eye to the lights to be compared, is enough to lead one seriously to question whether the method of flicker can be safely used in the work of heterochromatic photometry, at least not without calibration, and perhaps not without an amount of calibration which is in itself prohibitive of the use of the method in practical work. The third point will be covered in the following way. (1) It will be pointed out that the only method that has thus far been used as a standard with which to compare the method of flicker has been the equality of brightness method. The selection of this method as a standard has been recommended among others by Whitman, Wilde, and Schenck, and a comparison of the results of the two methods, more or less complete, has been made by a number of experimenters. And (2) it will be shown both from our own work and from a very great preponderance of the work done by others who have made the comparison, that the results by the method of flicker do not agree in the average with those obtained by the equality of brightness method; and, therefore, that justification for the adoption of the method of flicker can not yet, at least, be fairly claimed through its agreement in result with the equality of brightness method.

The Equality of Brightness Method.—With regard to sensitivity in the photometry of lights of different color, the equality of brightness method has the following disadvantages. (1) Small differences in luminosity can not be detected because the actual difference present is masked by the difference in color quality. (2) Results for a given observer can not be reproduced within a small limit of variation, because the ability to do this in turn presupposes the ability to detect small differences which, as has just been stated, can not be done. (3) Results can not be reproduced from observer to observer within a small limit of variation because (*a*) the sensitivity to color varies more among observers than does, for example, the sensitivity to brightness, hence there is a variable amount of the disturbing factor of color present for different observers; and (*b*) because the standard or pattern for the judgment of equality differs

more from individual to individual when the factor of color is present than when it is not. That is, in any photometric judgment the observer must decide for himself what he will call equality and make all his judgments conform to this pattern or standard. When color is present to interfere with the judgment of equality, the selection of this standard varies more for different observers than it does when no color is present. With regard to all the points on which sensitivity depends, therefore, the equality of brightness method may be said to possess a low degree of sensitivity.

The Method of Flicker.—The method of flicker possesses greater sensitivity than the equality of brightness method. That is, smaller differences in the luminosity of the photometric surfaces can be detected, and the judgment of equality is surer and more reproducible.[1] This is because the disturbing factor of color difference in the impressions to be compared is eliminated from the judgment. That is, instead of being given simultaneously, the stimuli are given in succession and at such a rate that all color differences between them disappear, and the brightness impressions are permitted to develop in sensation unobscured by differences in color quality.

The use of the phenomenon of flicker to detect a difference in brightness between two illuminated surfaces can best be understood possibly by considering the phenomena that take place when successive impressions of colored and colorless light are made upon the retina at different rates of speed. When the retina is exposed successively to colorless lights differing in brightness, the following phenomena take place. When the rate of succession is low, the impressions remain

[1] This higher degree of reproducibility can be claimed perhaps only for the judgments given by a single observer. It does not seem to obtain to any considerable extent, so far as results are available for comparison, when results are compared from observer to observer. For example, in a group of eighteen observers Ives gets differences as great as 159 per cent. for .481 μ, 114 per cent. for .498 μ, 26 per cent. for .518 μ. 8 per cent. for .537 μ; 13 per cent. for .556 μ; 10 per cent. for .576 μ; 28 per cent. for .595 μ, 65 per cent. for .615 μ; 86 per cent. for .635 μ; and 122 per cent. for .655 μ. The percentage of average variation from the mean for these observers is 17 per cent for .481 μ; 13.4 per cent. for .498 μ; 6 per cent. for .518 μ; 3 per cent. for .537 μ; 2.75 per cent. for .556 μ; 2.2 per cent. for .576 μ; 5.4 per cent. for .595 μ; 9.5 per cent. for .615 μ; 13.2 per cent. for .635 μ; and 19.3 per cent. for .655 μ. (*Philos. Mag.*, 1912, 4, Ser. 6, pp. 853–863.)

more or less separate and distinct. At rates higher than this, we have in order Fechner's colors,[1] flicker, and the fusion of the two impressions into a uniform gray. When the eye is exposed successively to colored and colorless light, the following phenomena take place. At low rates, we have again the more or less separate successions of the two impressions. At rates slightly higher than this, we have first a phenomenon that may be called by analogy color flicker, and then an intermingling of color and brightness flicker. At still higher rates we have color fusion, brightness flicker, and complete color and brightness fusion. Thus, both in case of colored and colorless light, brightness flicker seems to be a phenomenon due solely to the succession at certain rates of speed of impressions differing in luminosity or brightness. Moreover, the phenomenon is very sensitive to changes in the luminosity of the successive impressions. That is, a very slight change in one of the impressions will produce flicker when there is no flicker, or will cause a noticeable change in its amount when there is flicker. Flicker thus becomes a very sensitive means of detecting brightness difference. This sensitivity, however, is not so great in case of colored as it is in case of colorless light. It would in fact in all probability be very low were it not for the fortunate fact that color fusion takes place at a very much lower rate of succession than brightness fusion.

Concerning the ease and sureness of making the judgment, then, the case with regard to the method of flicker may be summed up as follows: By giving the impressions to be compared to the retina successively at a certain rate of speed, the disturbing element of color difference, which so interferes with the detection of brightness difference when the impressions are given simultaneously, is eliminated, and the phenomenon of brightness flicker stands out clearly in a field uniform as to color quality. That is, by using a method of successive impressions we have succeeded in eliminating the

[1] Fechner's colors are best observed when the successions are made by rotating discs made up of white and black sectors, or by discs specially constructed for the purpose. This phenomenon occurs at a rate of speed near the upper limit required to give separate impressions, and consists of impressions of color mingled with the more or less separate impressions given by the white and black sectors.

feature that renders the comparison of the brightness of the simultaneous impressions so difficult to make, namely, the difference in color quality between the impressions to be compared. The judgment, then, is easy, and the principle on which the equalization is based seems to be clear. The method has come to have many supporters, but other things besides the sureness of judgment must be taken into account. This brings us to a consideration of our second point, namely, the method of flicker when applied to the photometry of lights of different color does not seem to possess the sureness of principle needed to meet the requirements of a satisfactory method. We have two reasons for making this assertion. In the first place, as we have already stated, at the rate of speed at which the impressions are given in the method of flicker, the eye is very much underexposed to its stimulus. And in the second place, flicker, the phenomenon on which the equalization is based at the photometric surface, is subject to many variations depending upon a number of factors the bearing of which on the application of the phenomenon to photometry, has not in all cases been adequately studied, and in some cases not even recognized. A few of these may be suggested in passing. (1) The intensity of illumination and the influence it exerts on the speed of alternation that has to be used in order to give the method maximum sensitivity. (2) The different rates of speed required for the fusion of the different colors, and the varying lower limit this difference puts upon the rates of speed that can be used. (3) The effect of the saturation of the colors used on the fusion rate. (4) The effect of field size. (5) The effect of the ratio of the time of exposure of the eye to the lights to be compared; etc. A better knowledge than we now have of the effect of these factors is, the writers believe, of fundamental importance in the employment of the phenomenon of flicker in the photometry of lights of different colors. At a later date they hope to report the results of a systematic study of these factors. In the present paper, the effect of only one of them will be considered, namely, the ratio of the time of exposure of the eye to the lights to be compared. An investigation of this

point alone is enough to lead one seriously to question whether the method of flicker can safely be used in the work of heterochromatic photometry, at least not without calibration, and perhaps not without an amount of calibration which is in itself prohibitive of the use of the method in practical work.

The Action of Light on the Eye under the Conditions Imposed by the Method of Flicker.

Both of the above points will probably be more easily understood if a brief consideration is given to the way the eye responds to colored and colorless lights when the impressions are given to it in the manner they are given in the method of flicker. The eye is not an ideal sense organ, that is, it does not respond at once with its full intensity of sensation at the beginning of stimulation, nor does the sensation cease with the cessation of stimulation. It takes, for example, an interval of time for the sensation proper to a given stimulus to rise to its maximum; and also an interval to die away after the stimulation has ceased, depending for its length upon several factors.[1]

The interval of time required for a sensation to rise to its maximum will be called in this paper the development time of sensation. Plateau in 1834[2] first expressed the belief that

[1] There are two phases to this after-effect, positive and negative. The positive alone concerns us here. In this phase, which is often called the persistence of vision, the original sensation tends to persist in its original color and brightness. More accurately described, however, it rapidly loses in color and rapidly darkens. In the negative phase there is a brightness reversal, that is, what is light in the original sensation becomes dark, and the color changes to the complementary color. The negative phase is much longer than the positive. The length of the positive depends upon many factors: the intensity of the stimulus, the time of exposure of the eye to the stimulus, the state of adaptation of the eye, the general illumination of the field of vision, the brightness of the local preëxposure and post-exposure, etc. Unless the eye is put under very especial conditions of stimulation, the duration of the positive phase is very short indeed, in fact, momentary. For a further discussion of this point with reference to the method of flicker, see appendix.

[2] As early as the time of Bacon it was noted that there is a period of inertia in vision. ("At in visu (cujus actio est pernicissima) liquet etiam requiri ad eum actuandum momenta certa temporis: idque probatur ex iis, quae propter motus velocitatem non cernunter; ut ex latione pilae ex sclopeto. Velocior enim est praetervolatio pilae, quam impressio speciei ejus quae deferri poterat ad visum."—'Novum Organum,' lib. II., Aph. XLVI.). Later Beudant ('Essai d'un Cours Elementaire

color sensation does not come at once to its maximum. He, and later Fick[1] in 1863, showed that when a sector of white paper passes very rapidly only once before the eye it looks to be a dark gray. With the experiments of Exner in 1868, the work of determining the development time of visual sensation was definitely begun. Different methods of making the determination have been used by different investigators, and different results have been obtained. There is, however, among the different results a certain amount of agreement. At least the order of magnitude of the development time can be fixed within certain limits. The chief points of interest in these investigations have been (1) to compare the development time of the different sensations of color with each other and with that of colorless sensation; and (2) to determine whether the intensity of the stimulus has any effect upon the development time. All who have made the comparison have found that each of the color sensations has a development time different from the colorless sensations; all with the exception of Dürr and Berliner, that each of the colors has a different development time; and all with the exception of Dürr, that an increase of intensity shortens to some extent the development time of all sensations.

A table (Table I.) has been prepared showing the development time obtained by each of these men for the different

et General des Sciences Physique: Partie Physique,' p. 489, 3me edition) also stated that an object which moves with extreme rapidity before the eye is not perceived because impressions are not made on the eye instantly. Plateau ('Nouveaux Memoirs de l'Academie Royale des Sciences et Belles Lettres de Bruxelles,' 1834, *8*, p. 53) made the observation that when a bit of white paper passes very rapidly before the eye, it appears not white but gray. He was the first to express the belief that color sensation also does not come at once to its maximum of intensity. Swan (*Trans. Roy. Soc. Edinb.*, 1849, *16*, pp. 581–603) observed that the "light of the sky seen immediately over a ball in its descent through the air, seemed less bright than at those parts of the retina where the action of light had not been interrupted by the passage of the dark body"; and conducted some experiments to determine the intensity of light sensation with short exposures. Exposing the eye to lights of different intensities for intervals ranging from 1/100 to 1/16 of a second, colorless 'lights of different intensity produce like portions of their total effect on the eye in equal times.' While he does not directly determine the interval required for the light sensation to come to its maximum, he estimates it from the results of his experiments with short exposures to be about 1/10 of a second.

[1] Fick, A. *Archiv für Anatomie und Physiologie*, 1863, p. 739.

Table I

Showing a Comparison of the Development Time of Visual Sensation with the Average Time of Exposure of the Eye to Its Stimulus Used in our Experiments with the Method of Flicker.

		Sensation	Development Time	Average Time of Exposure of Color by Method of Flicker
Exner[1]	1868	White	5 intensities: .118–2.87 sec.	.0178 sec., when the value of the colored sector was 180°.
Kunkel[2]	1874	Different colors	.057–.133	
Charpentier[3]	1887	White,	5 intensities .014–.049	
Lough[4]	1896	White,	5 intensities .090–.148	
Dürr[5]	1902	White,	2 intensities: .266	
		Different colors	.541	
Martius[6]	1902	White	6 intensities: .013–.093	.0213 sec., when the value of the colored sector ranged from 45°–315°.
		Different colors	.020–.090	
Broca and Sulzer[7]	1903	White	8 intensities: .031–.125	
		Different colors	.07 –.125	
McDougall.[8]	1904	White	12 intensities: .049–.2	
		Different colors	.100–.108	
Büchner[9]	1906	White	3 intensities: .033–.230	
Berliner[10]	1907	Different colors	.130	

[1] Exner, S., 'Ueber die zu einer Gesichtswahrnehmung nöthige Zeit.,' *Sitzungsberichte der Kaiserlichen Akademie der Wissenschaften*, Math.-Phys. Classe, 1868, *58*, pp. 601–632.

[2] Kunkel, A., 'Ueber die Abhängigkeit der Farbenempfindung von der Zeit,' *Pflüger's Archiv*, 1874, *9*, p. 197.

[3] Charpentier, 'Sur la periode d'addition des impressions illuminismes,' *Comptes Rendus Societé de Biologie*, 1887, *4*, pp. 192–194.

[4] Lough, 'The Relations of Intensity to Duration of Stimulation in Our Sensations of Light,' Psychological Review, 1896, *3*, pp. 484–492.

[5] Dürr, E., 'Ueber das Ansteigen der Netzhauterregung,' *Philosophische Studien*, 1901–1903, *18*, pp. 215–273.

[6] Martius, G., 'Ueber die Dauer der Lichtempfindungen,' *Beiträge zur Psychologie und Philosophie*, Leipzig, 1902, 1, Heft 3.

[7] Broca, A., and Sulzer, D., *Comptes Rendus der Séances de l'Académie des Sciences*, 1902, *134*, pp. 831–834; 1903, *137*, pp. 944–946; 977–979; and 1046–1049.

[8] McDougall, W., 'The Variation of the Intensity of Visual Sensation with the Duration of the Stimulus,' *British Journal of Psychology*, 1904–1905, 1, pp. 151–189.

[9] Büchner, M., 'Ueber das Ansteigen der Helligkeitserregung,' *Psychologische Studien*, 1906–1907, *2*, pp. 1–29.

colored and colorless sensations; and, for comparative purposes, the average exposure time that was used in our experiments for all the colors in the determination of their brightness by the method of flicker. In choosing this time of exposure for the method of flicker, in order to secure for the method the greatest possible sensitivity, we used the slowest rate of succession of colored and colorless sectors that could be employed.

An inspection of this table will show that while the results for the development time of sensation differ quite a little among themselves, they agree in one very important particular, namely, they are all much greater than are the intervals that are used in the longest exposures that are permissible by the method of flicker. That is, by the method of flicker, the eye is very much underexposed to its stimulus. The effect of this under exposure is obviously to cause a reduction in the intensity of sensation. That is, the rate of succession of impressions used in the method of flicker is too fast for the single impressions to arouse their maximum effect in sensation and too slow for the successive impressions to add or summate as much as they would need to do to cause the intensity of the sensation aroused by each light to rise to its full value, or perhaps even to rise to a higher value than would be given by the individual exposures. In fact as will be shown in an appendix to this paper the sensation can not be expected to rise to its full value through summation if the Talbot-Plateau law be true, however rapid is the rate of succession of the individual impressions (see appendix). Even when a rate is reached at which complete fusion takes place, both for the color and brightness components in sensation, there is according to the Talbot-

[10] Berliner, 'Der Ansteig der reinen Farbenerregung im Sehorgan,' *Psychologische Studien*, 1907, *3*, pp. 91–155.

W. Swan in an article entitled 'On the Gradual Production of Luminous Impressions on the Eye; Part II., being a description of an instrument for producing isolated luminous impressions on the eye of extremely short duration, and for measuring their intensity,' *Trans. Roy. Soc. Edinb.*, 1861, *2*, pp. 33–40, has described a very ingenious but complicated apparatus for getting short periods of stimulation of the retina, but apparently neither he nor any one else has ever used the apparatus described.

Plateau law, a reduction in the intensity of each sensation which is the same as would be gotten were the intensity of each light to be reduced in proportion to the time of exposure of that light to the total time of exposure of both lights, and no further increase in the rate of succession produces any change in the effect.[1] The possibility then of the sensations which, as is shown by the work on development times, are unequal for the single exposures used in the method of flicker, reaching equality by rising to their full value seems to be ruled out. In terms of the Talbot-Plateau law they could not reach their full intensity through an effect of summation, however fast the rate of succession be made,

[1] Ewald ("Versuche zur Analyse der Licht- und Farbenreaktionen eines Wirbellosen" (*Daphnia pulex*), *Ztschr. f. Psychol. u. Physiol. d. Sinnes.*, 1914, 48, pp. 285–325; and "The Applicability of the Photochemical Energy Law to Light Reactions in Animals," *Science*, 1913, 38, pp. 236–238) has made an interesting contribution with regard to the effect of the intermittent action of light on the eye which it may not be out of place to mention here. The facetted eye of the daphnia was used in his experiments. When exposed to light this eye responds by turning towards the light, and when lights of different intensities are used it turns towards the stronger light. After having determined the sensitivity of this response to difference in intensity of light by exposing the eye to a number of lights of different intensities acting continuously on the eye, he undertook to make a comparison of the effect of light acting continuously and intermittently. The intermittence was gotten by rotating a sectored disc in front of one of the lights. The lights were so chosen that the same amount of energy acted upon the eye in a given unit of time from both the continuous and intermittent sources. That is if a ratio of total open to closed sector of the value 1/10 was used, the light in front of which these sectors were rotated was made ten times as intense as the light acting continuously. The sectored disc was then rotated at different speeds. When a speed of 30 revolutions per second was attained the eye remained stationary. That is at this speed of rotation the two lights produced equal effects on the eye,—which is, of course, no more than a demonstration of the Talbot-Plateau law for the primitive eye. But when the speed was made slower than this, the eye invariably turned towards the light which was acting continuously. That is when the rate at which the impressions were given to the eye was made slower the result was to weaken the effect on the eye even though the same amount of light was received by the eye in a unit of time in both cases. Ewald's results show then that, so far as the primitive eye is concerned, when light impressions are given to the eye at certain high rates of succession (analogous to the fusion rates for the human eye) there is a reduction in the amount of response aroused which is the same as would be produced were the intensity of the light reduced by an amount proportional to the ratio of the time of exposure to the light to the total time of the observation; and when they are given to the eye at rates slower than these the effect on the eye is the same as if the light acting on it had been still further reduced in intensity.

let alone attain it at the rates which are employed in the method of flicker.[1]

[1] There seems to be only one other possibility that the method of flicker should give the true photometric balance between lights of different color values, namely, that the sensations aroused should reach equality at some value lower than the full value. That this is extremely improbable is shown by the following consideration. The weaker sensation or the sensation which has the slower rate of development for a single exposure would have to rise in value because of summation effect resulting from the succession of exposures until it became equal to the stronger sensation. To produce any effect of summation each individual impression would have to last over in sensation until the next impression of its kind is received which, since the impressions alternate, would be the next impression but one. And to produce the particular effect required here, not only would each excitation have to last over until the next one is aroused, but the weaker one would have to last over more strongly than the stronger one, else the effect of the summation would not be to produce the gain of the weaker on the stronger which is required to bring the two to the true photometric balance. That is, the advocate of this point of view would say that even though for the single exposure one color is weighted more than the other, the effect of this is obliterated in a succession of impressions and the two rise to equal value, because the weaker sensation would carry over more strongly hence would gain more relatively in the process of summating than would the stronger sensation. This is not at all in accord with the experimental evidence available at this time on the relation of the positive after-effect or persistence of sensation to the original sensation. Goldschmidt ("Quantitive Untersuchungen über positive Nachbilder," *Psych. Studien*, 1910, *6*, pp. 159–252) and others show, for example, that the stronger the original sensation, the more strongly does it tend to carry over after the light is cut off. Goldschmidt also concludes from his experiments, which is a very important point for this discussion, that the tendency of the sensation to carry over is, so far as its brightness is concerned, independent of the color. That is, suppose that a photometric balance was obtained for green and red lights of comparatively high intensities by the method of flicker. Then according to Broca and Sulzer's curves, also the results obtained in this laboratory, green would attain to a higher brightness value for the single exposure than would be attained by red. Hence if green is not to be overestimated by the method of flicker, red must carry over more strongly as the impressions succeed each other than does green, and thus make up by a summation effect the deficiency shown in the single exposure. But according to Goldschmidt's results this greater tendency to carry over could not be assumed for red, either because of its color value or because of its weaker intensity, and there is no other aspect of the sensation which could have any bearing on the question in hand. Moreover, this hypothesis is rendered still more untenable by the experimental fact that the situation at low intensities is reversed. That is, at low intensities red, as shown by the curves for difference in lag (see Fig. 2, p. 127), attains to a higher value than green for the single exposure. Then if red is not to be overestimated by the method of flicker and in direct proportion to the values given to the two sensations in the single exposure, green must be carried over more strongly in the succession of impressions than is red. The explanation of both of these points would require not only that the color value of the stimulus exerts an influence on the carrying over of the brightness aspect of the sensation, but that this influence reverses in passing from high to low intensities. For a discussion of how highly improbable it is for the rates of succession used in the method of flicker that one impression could last over until the next impression but one is received in any amount that could be of considerable consequence to the method, see appendix.

It seems fair to conclude, then, that instead of getting by the method of flicker the sensations that should be aroused by the lights with which we are working, we get sensations of lower intensity. But it may be asked what if there is a reduction of the intensity of the impressions received? Equalization is all we are working for and the intensity of both impressions is reduced. Is it not possible, therefore, to find a ratio of time of exposure to each light such that the amount of reduction in the intensity of both impressions will be equal? This would be comparatively simple if the rate of development for all the colored were the same as for all the colorless sensations. The intervals of exposure could be made equal as is ordinarily done when sectored discs are used and as apparently must be done when the exposures are given by means of a rotating prism. But the development time for color sensation is not the same as for colorless sensation, and, moreover, the consensus of evidence is that the rate of development is not the same for any two of the color sensations. Thus from the standpoint of the unequal reduction in intensities produced by the method of flicker, the task of selecting a proper ratio of exposure time of colored to colorless light, in case of the different colors, is one that requires a great deal of accurate knowledge if the method is to have the sureness of principle needed,—more, the writers think, than we now possess.[1]

[1] One scarcely needs point out in this regard that there is apparently no point in the intensity scale for which a given reduction in intensity for colored light gives the same change in luminosity in sensation that it does for white light. Beginning with the spectrum of fully saturated colors and comparing the effect of reduction by equal amounts of colored and white lights equal in photometric value, the blues and greens are found not to decrease in luminosity so fast as the white light, and the reds and yellows are found to decrease faster. Or as the phenomenon is ordinarily expressed, there is a relative lightening of the blues and greens and a relative darkening of the reds and yellows. Nor is the phenomenon of unequal change confined to the lower intensities. It is more striking for these intensities, but it occurs also for the higher intensities. This conclusion is drawn from the statement made by several writers that beginning with the spectrum of fully saturated colors and increasing the intensity of light, all the colors are found to tend towards white, and in so doing to change their luminosities at different rates. (For example, see Helmholtz, H., 'Ueber Hrn. D. Brewster's neue Analyse des Sonnenlichts,' *Pogg. Ann.*, 1852, *86*, p. 520; also *Handbuch der physiologischen Optik*, zw. Aufl., 1896, pp. 465–466; Chodin, A., 'Ueber die Abhängigkeit der Farrbenempfindungen von der Lichtstärke,' Sammlung physiologischer Abhandlungen von Preyer, 1877, *1*, p. 33 ff.; Brücke, E., 'Ueber einige

We have discussed here, moreover, the effect of underexposure at only one rate of rotation of the exposure apparatus. The situation becomes still more complicated when this rate is changed. If it were changed, as it must be to preserve the sensitivity of the method in passing from high to low illumination, the whole scale of magnitude of the underexposure would change, and a shift in the relative evaluation of the luminosities of the different colors might very well be expected from the shape of the sensation curves as they rise to their maximum. In fact this shift is found in the work of previous investigators[1] who have made the comparison at

Empfindungen im Gebiete der Sehnerven,' Sitzungsber. der Wiener Akademie, Math.-Natur. Klasse, 1878, *77*, Abth. 3, p. 63.) As we have already stated, however (p. 113), we do not mean to draw too close an analogy here between the effect on the brightness of sensation produced by keeping the intensity of light constant and reducing the time of exposure of the eye to the light, and the effect of keeping the time of exposure of the eye to the light constant and reducing the intensity. The degree to which the analogy holds can scarcely be considered as fixed until more work is done showing the way in which the luminosity curves for the different colors rise to their maximum as the time of exposure of the eye to the different colored lights is increased.

[1] See, for example, the phenomenon called by Ives the "reverse Purkinje" effect (*Philos. Mag.*, 1912, *24*, Ser. 6, pp. 170–173); later demonstrated and discussed by Luckiesch (*Electrical World*, March 22, 1913, p. 620). These writers have found that the red end of the spectrum shows a relatively higher luminosity value as compared with the green end by the method of flicker at low than at high illuminations. From the shape of Broca and Sulzer's curves for the rise of visual sensation, to its maximum, for example, this result might very well be due to the difference in the relative luminosity value of the colors caused by the difference in the length of exposure given to the eye in the method of flicker at the faster rates of speed required for the higher illuminations and at the slower rates for lower illuminations. That is, the longer exposures given by the slower speeds of rotation allow the colors to attain a higher intensity. For example, the speeds used by Ives for what he calls 10 Illumination Units range, for the different colors for five observers, from 7 to 10 cycles per second, and for 250 Illumination Units from 10 to 22 cycles per second.

Broca and Sulzer's curves (Fig. 1) are appended here for one order of intensity of stimulus (*Comptes Rendus*, 1903, *137*, p. 978. For other intensities see p. 945). The curves given were selected because they alone show a comparison between the results for colored and white light. It will be seen from these curves that for exposures less than .07 sec. (approximate value), blue and green rise to a higher value than red; for exposures ranging from .07 to .11 sec., blue rises to a higher value than red, and red higher than green; and for exposures ranging from .11 sec. to about .25 sec., red rises to a higher value than blue or green.

There is also a very strong probability that the relative lag in sensation for the different wave-lengths is not the same for lights of low intensity as for lights of higher intensities. In fact the results that have been obtained so far in this laboratory in determining the development time of the sensations aroused by red, yellow, green, and

intensities low enough to necessitate a decided reduction in speed of rotation. And that the shift is different from the normal effect on the brightness of the colors produced by a decrease of illumination, is shown by the fact that according to the results of these investigators it is in a different direction from that given by the equality of brightness method. Moreover, in the later paper it will be shown that a change in this evaluation amounting to several times the smallest difference in luminosity that can be detected by the method, is also produced by working the reverse variation, that is, by keeping the rate of rotation constant and changing the ratio of value of colored to colorless sector. It is difficult, therefore, to avoid the conclusion that the type of exposure used in the method of flicker is an important factor in the cause of its disagreement with the results obtained by other methods.

blue lights of spectrum purity show that at low intensities red and yellow rise more rapidly in photometric value than green and blue. This result is quite marked in those parts of the curves representing an exposure time of the same order of magnitude as is used in the method of flicker. In order to show this point we have appended here

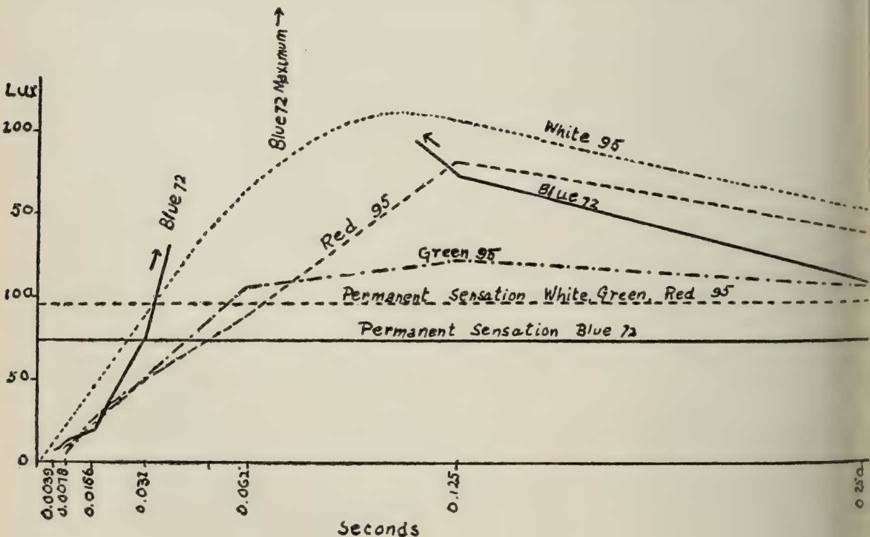

Fig. 1

three curves representing the relative rates of development of red, yellow, green, and blue at intensities which we will designate for the present as low and intermediate; and of red, yellow, and green for a higher intensity. These determinations were made by

Reëxamining the case, then, with regard to the underexposure of the eye by the method of flicker, we find that the short exposure times necessary to the method cause a re-

M. A. Bills of this laboratory. Later, results will be given for red, green, blue, and yellow at a number of intensities, and specifications will be made of the intensities employed in both photometric and radiometric units. The colored lights used in determining the curves given below were obtained from a spectrum of good definition and were in each case equal in photometric value, as they should be if results are to be used in interpreting the action of light on the eye under the conditions imposed by the

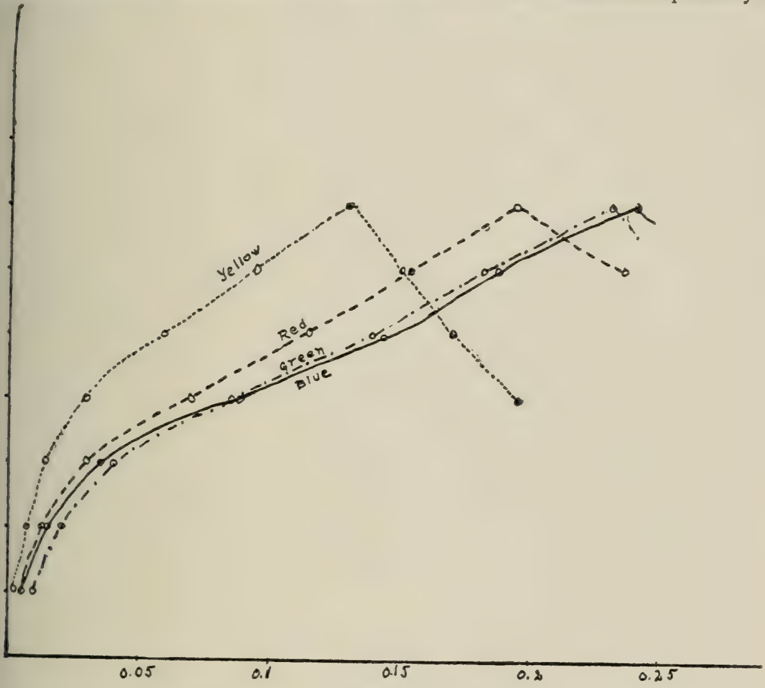

FIG. 2

method of flicker when the photometric balance is attained. In constructing these curves time of exposure is plotted along the abscissa and brightness of color along the ordinate. The curves in Fig. 2 are for the low intensity; in Fig. 3 for the intermediate intensity; and in Fig. 4 for the higher intensity.

It is very probable that there is considerable individual difference in the amount and distribution of lag. A rigid test of the correspondence of difference in lag to the direction of deviation of results gotten by the method of flicker from those obtained by the equality of brightness method would require that the photometric determinations and the determination of lag should be made for a given quality and intensity of light by the same observer.

If it should be found that there is an individual difference in the amount and distribution of lag, the result would supplement very nicely the explanation why a much higher degree of reproducibility is gotten by the method of flicker than by the method

duction in the action of the standard and comparison lights on the eye. If this reduction were equal in amount, quite enough difficulty would be encountered. But it is not

of equality of brightness only when the results of a single observer are considered (see footnote, p. 115). That is since the factor of color difference which so disturbs the judgment in the equality of brightness method is eliminated in the method of flicker, we should get correspondingly a higher degree of reproducibility for a single observer and for different observers, were there not some factor present in the method of flicker and not in the equality of brightness method, which varies from individual to individual. So supplemented the explanation would be as follows. In the method of flicker the

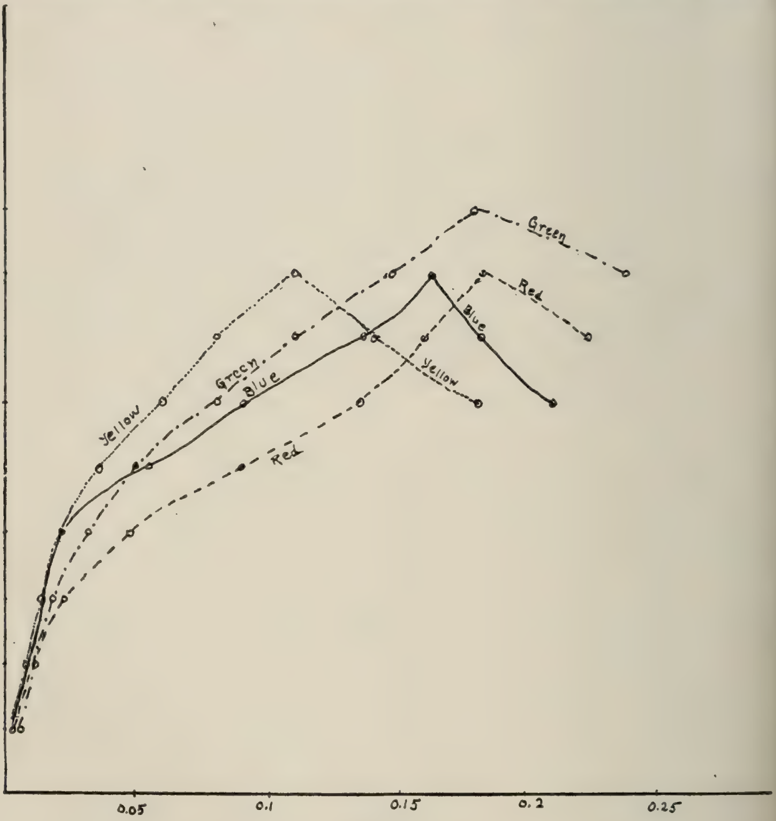

FIG. 3

judgment for a single observer shows a higher degree of reproducibility than in the equality of brightness method because of the elimination of the disturbing factor o color difference; but a false balance is established by the method, the deviation from the true balance depending in direction and amount for different observers upon the difference in the amount and distribution of lag in the rise of the sensations towards the maximum. The difference in the amount and direction of this deviation from the true balance from observer to observer is the cause of the relatively low degree of reproducibility of results when the work of different observers is compared.

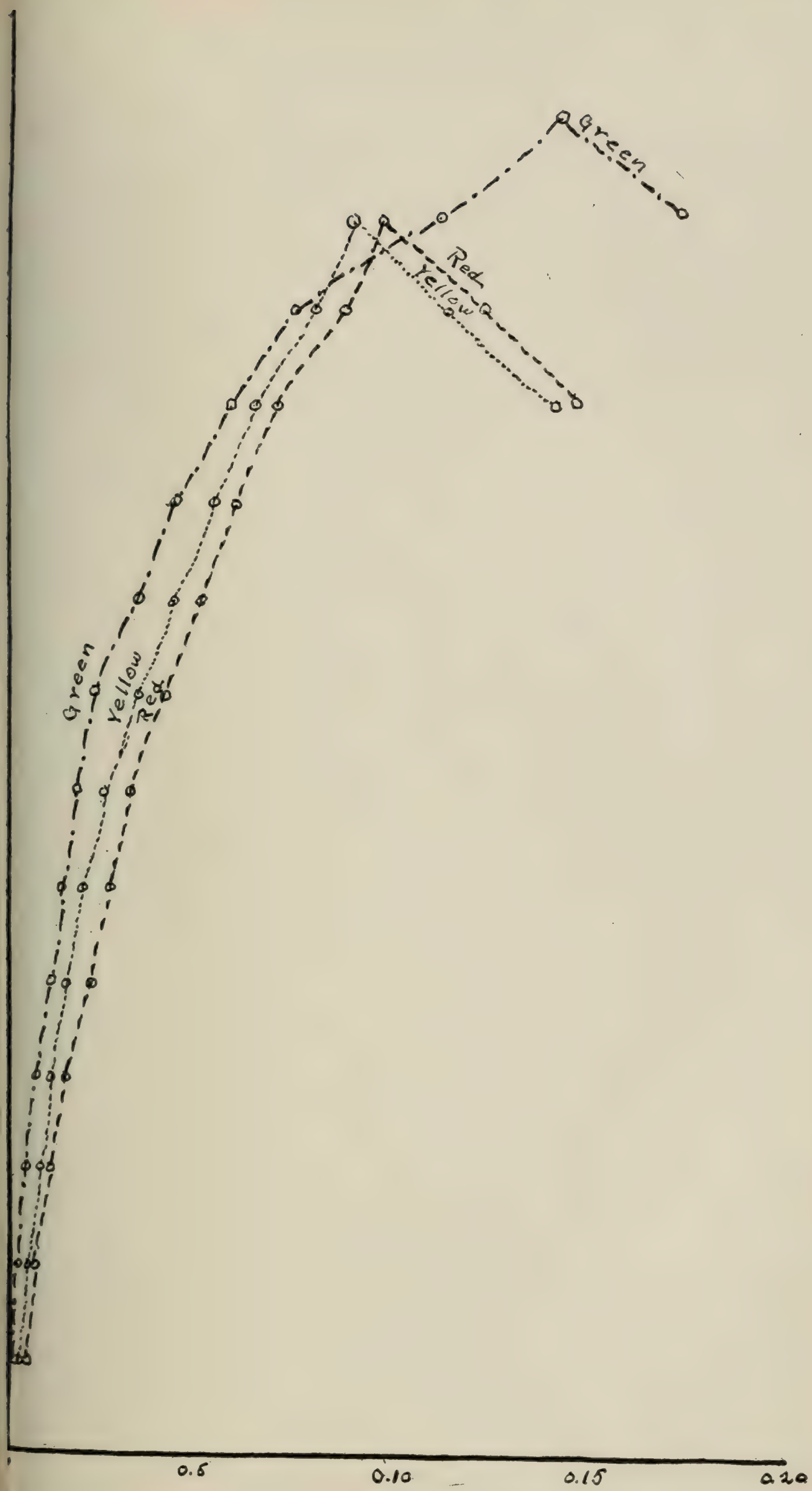

FIG. 4

equal in amount, and we have no adequate information as to the amount of the inequality. Until we have more information with regard to the amount of the reduction and the effect it produces, any successful attempt to regulate the relative duration of the exposure to colored and colorless light, even for a single color at a single intensity, can scarcely be more than the result of chance. Surely to expect to accomplish this for all intensities of all colors by a single ratio of exposure, more especially by means of a 1:1 ratio, as has been the practice in the past, is, it would seem to the writers, to ignore the sensation principles which underlie the method. Obviously this ratio requires calibration, and to give the method the sureness of principle required, it would seem that the calibration might have to be made for each color at the particular intensity at which the work is to be done. This calibration might possibly be accomplished by means of an accurate knowledge, if that knowledge could be secured in sufficient detail, of the temporal course of visual sensation as it rises to its maximum for the given intensity of light used; or it might be done by comparing the results obtained by the method of flicker with the results obtained by some other method adopted as a standard. So far the tendency seems to have been to look for this standard within the subject of photometry itself. As has already been stated, several writers have signified a desire to make the equality of brightness method a standard, and comparisons have been made of the results obtained by the method of flicker and the equality of brightness method.

A consideration of the results of these comparisons together with the data collected by one of the writers in ten years use of the flicker and equality of brightness methods in making the brightness matches needed for the work in color sensitivity, has influenced us to open the question anew in the interests of the work on color sensitivity. In the work with these two methods all done at comparatively high illuminations and with a large number of observers, agreement has been rare. For this reason the chief incentive to make the present study has not been to establish disagreement, but to investigate

further the causes of disagreement. The results of this study seem to indicate that the type of exposure of the eye to its stimulus by the method of flicker is an important cause of disagreement.

So much for the theoretical considerations relating to the method of flicker. To test the accuracy of some of the more important points that have come up, a plan of experimentation has been formulated and in part carried out. So far as the results of that experimentation will be reported upon in this paper, the following things will be shown. (1) By comparing the time required for the sensations aroused by colored and colorless light to reach their maximum of intensity, we have already shown that as a general case the eye is very much underexposed to its stimulus by the method of flicker, and we have concluded that the effect of this underexposure on the brightness component of sensation will be unequal in amount for colored and colorless light, and should lead, therefore, to a false estimation of the brightness of the colors. That this conclusion is justified so far as our work is concerned, will be demonstrated in part by comparing the results of the method of flicker with those obtained by the equality of brightness method, in which case the eye is fully exposed to its stimulus, and showing that for the method of flicker there is for our observers for the intensities of light used and for the rate of rotation of the photometer head required for these intensities, a characteristic underestimation of the brightness of red and yellow and overestimation of the brightness of blue and green. That this characteristic deviation is due to the type of exposure used in the method of flicker and not to some other factor will be further shown in the consideration of our second point. (2) We have said that the ratio of the time of exposure should be considered as a factor influencing the results obtained by the method of flicker. In order to confirm this judgment of the case, we have varied this ratio, keeping the other conditions constant, and have found that a corresponding variation is produced in the results. That is, by changing the value of the colored and colorless sectors in the rotating disc we have used to

regulate the time of exposure in the method of flicker, corresponding variations are obtained in the characteristic underestimations of red and yellow and the overestimations of blue and green. These variations, it will be shown, moreover, are very much greater than the changes in luminosity that are required to be detected by the method of flicker, and are, therefore, worthy of being taken into account in an evaluation of the usefulness of the method, whatever method be adopted as a standard for comparison. And (3) we have contended that if the equality of brightness method be adopted as the standard for work in color photometry, the method of flicker does not satisfy the requirements, for it does not give results which agree in the average with those obtained by the equality of brightness method. This will be shown both from results of our own work and from a preponderance of the work done by others who have made the comparison. In our own work the comparison has been made for a series of intensities which may be considered as at least fairly representative of the higher intensities, they being considered more favorable to agreement by Dr. Ives.[1] Especial care has been taken in this series to duplicate at one point the intensity which Dr. Ives finds the most favorable to agreement.

The remainder of the paper will be taken up with the demonstration of these three points.

I. The Underestimation of the Luminosities of Red and Yellow and the Overestimation of the Luminosities of Blue and Green

Special tables have not been prepared for this point because the results can readily be seen in the tables for points II. and III. In these tables taken collectively the comparison will be shown for a representative series of variations, both of the ratio of the time of exposure to colored and colorless light and of the intensity of the lights employed. In every case underestimation is found to be characteristic for red and yellow, and overestimation for blue and green.

[1] Ives, H. E., 'Studies in the Photometry of Lights of Different Colors, *Philos. Mag.*, 1912, *24*, Ser. 6, pp. 149–188.

II. The Variation of the Ratio of the Time of Exposure to the Colored and Colorless Light Causes a Corresponding Variation in the Characteristic Underestimation of Red and Yellow and Overestimation of Blue and Green

As has already been stated, the work under this heading has been undertaken in part to show the preceding point, and in part to show that the amount of this underestimation and overestimation is a variable function of the ratio of the time of exposure to the colored and the colorless light. The effect of the variation was determined both when the com- parison was made between colored and colorless pigment surfaces, and between colored and colorless lights. For the pigment surfaces the standard red, green, blue, yellow, white, and black of the Hering series of papers were used. For the colored lights, two sources have been used: the Wratton and Wainwright color filters, and the light of the spectrum. Since the work with the spectrum as source has not yet been inished, results will be given at this point from the work with he filters. Of these filters, only the *Alpha* and *Eta* were sed. The former transmits a band of red from the end of he spectrum to .65 μ, the latter, a band in the blue-green rom .52 μ to .465 μ. These two alone were used for the ollowing reasons: (1) They are fairly representative of the olors that show a relative change in luminosity with change f intensity. And (2) the yellow, green, and blue filters each ransmits components that undergo opposite luminosity hanges with a change of intensity of the source. That is, he best yellow of the series transmits also a green com- onent; the best green, a yellow component; and the best ue transmits some of the violet.

The photometric apparatus employed was for the sake of omparison made to conform very closely in its essential eatures to that described by Dr. Ives.[1] The general plan our apparatus is indicated in Fig. 5. It consists of a photo- eter bar carrying the standard white light (A), a second bar rrying the colored light (B), a sectored disc (C), and a

[1] Ives, H. E., *op. cit.*, p. 161.

screen (D) provided with a small aperture (O) through which the light comes to the eye. The standard white light was enclosed in a black light-proof box (E), which was provided

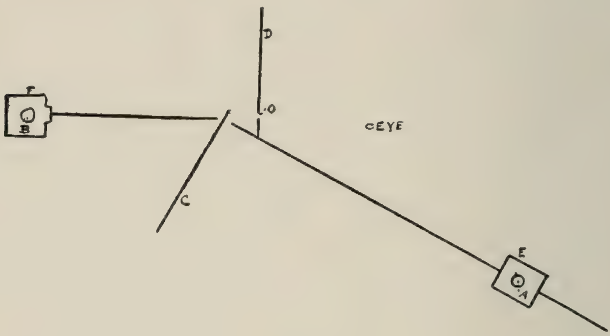

FIG. 5

in front with a circular opening 4 cm. in diameter for the transmission of the light. In passing to the sectored disc, the light was screened both from the observer's eye and from the colored source by black screens properly placed. The light which was passed through the colored filters was placed in a similar light-proof box (F) provided with an opening 4 cm. square for the transmission of the light. Above and below this opening were grooves into which the color filters were slid. The sectored discs were made of aluminum. The edges of these discs were carefully bevelled and the surface was kept freshly covered with magnesium oxide deposited from the burning metal. The aperture in the screen through which the light passed to the observer's eye was 3 mm. square. The visual angle subtended by this aperture at the observer's eye at 20 cm. distance was very small. A small angle was needed to guard against the unequal sensitivity of the central and paracentral portions of the retina to flicker, and against the difference in their brightness sensitivity to colored and colorless light. A 13-candle-power Mazda lamp was used as source for the colorless light, and 13-cp., 52-cp., and 130-cp. lamps for the colored light. These lamps were operated on a 110 D.C. circuit in series with an ammeter and finely graduated rheostat to guard against fluctuations in the current and

loss of efficiency in the lamps. Also fresh lamps were substituted at the beginning of each series of observations. As a check on the results obtained from these lamps, several series of observations were made using a standardized tungsten lamp, street series, 16.6-cp. operated at 11.43 volts by a storage battery for the colorless light, and a similar lamp of 67-cp. operated by a storage battery at 10.35 volts for the source of the colored light.

The method of making the flicker judgment was as follows: A preliminary determination was made of the approximate setting of the light which was being moved, to give equalization. The speed of rotation of the sectored disc was then reduced until flicker was obtained. The position of the light was again adjusted until no flicker was obtained, and so on. This variation in the speed of rotation of the disc and the position of the light was continued until the position was ascertained that gave no flicker for the lowest speed of rotation. The final determination of this point was made by moving the light in both directions until noticeable flicker was obtained, and taking the average of these two readings. The movement required to give flicker on either side of this average position ranged usually from 2 to 9 mm. depending to some extent upon the observer and the intensity of illumination used. Employing the above apparatus and method, results were obtained for the highest intensity of colored light used for a total open sector of 315°, 270°, 225°, 180°, and 45°; and for the other intensities, for a total open sector of 315°, 180°, and 45°. In making the comparisons by the equality of brightness method, the disc was rotated until one of its edges bisected horizontally the photometric field. The results are shown in Tables II.–V. They will be summarized briefly as follows: (1) For all values of open sector and for all intensities of light, there was an underestimation of the luminosity of the red light and an overestimation of the luminosity of the blue-green. (2) As the size of the open sector was decreased, there was a corresponding increase in the amount of the underestimation of the luminosity of the red for all the intensities employed, and of the overestimation

Table II

Observer *A*

Showing that the Underestimation of Red and the Overestimation of Blue-green is a Characteristic of the Method of Flicker, for Lights of the Intensity Used in this Work, and that the Amount of this Underestimation and Overestimation is a Variable Function of the Ratio of the Time of Exposure of the Eye to the Colored and the Colorless Light

Source of White Light	Source of Colored Light	Color	Equality of Brightness Method: Distance of White Light Giving Equality of Illumination	Flicker Method: Value of Colored Sector	Flicker Method: Distance of White Light Giving no Flicker	Difference by Equality of Brightness Method and by Flicker Method with 180° Open Sector	Change Produced by Varying Sectors	Amount of Change that Can be Detected by: Equality of Brightness Method	Amount of Change that Can be Detected by: Flicker Method	No. of Revolutions per Second, Flicker Method
13 cp.	13 cp. 151 cm.	Red	125.5 cm.	315°	133.9 cm.	−10.4 cm.	−3.4 cm.	3.5 cm.	.4 cm.	3.6
	distant from			180°	135.9				.3	4.7
	photometric			45°	137.3				.3	4.1
	screen	Blue-green	191	315°	183.45	+10.55	+5.4	4	.35	4.2
				180°	180.45				.35	6
				45°	178.05				.25	5.2
	52 cp. 151 cm.	Red	93.4	315°	102.05	−11.1	−4	3	.25	3.7
	distant from			180°	104.5				.2	5.9
	photometric			45°	106.05				.25	5.4
	screen	Blue-green	103	315°	94.5	+13	+5.65	4	.3	4.1
				180°	90				.3	6.1
				45°	88.85				.35	5.9
	130 cp. 89 cm.	Red	75.3	315°	82.9	− 9.7	−4	3	.4	6.3
	distant from			270°	84				.45	7.4
	photometric			225°	84.6				.4	9.2
	screen			180°	85				.5	9.2
				45°	86.9				.5	8.9
		Blue-green	82	315°	76	+ 7	+3.25	3.5	.5	6.6
				270°	77				.3	7.4
				225°	76.3				.3	8.1
				180°	75				.3	7.7
				45°	73.75				.35	7

Table II.—*Continued*

Observer *A*

Source of White Light	Source of Colored Light	Color	Equality of Brightness Method: Distance of White Light Giving Equality of Illumination	Flicker Method: Value of Colored Sector	Flicker Method: Distance of White Light Giving no Flicker	Difference by Equality of Brightness Method and by Flicker Method with 180° Open Sector	Change Produced by Varying Sectors	Amount of Change that Can Be Detected by Equality of Brightness Method	Amount of Change that Can Be Detected by Flicker Method	No. of Revolutions per Second, Flicker Method
16.6 cp. standard lamp	67 cp. standard lamp, 89 cm. distant from photometric screen	Red	86.5	315°	96.1	−13	−4.2	2.5	.5	6.1
				180°	99.5				.3	8.7
				45°	100.3				.4	8.2
		Blue-green	85	315°	77.4	+11.55	+5.4	3	.3	5.6
				180°	73.45				.45	7.2
				45°	72				.5	6.9

Table III

Observer *B*

13 cp.	52 cp. 151 cm. distant from photometric screen	Red	88 cm.	315°	99.18 cm.	−17.5 cm.	−8.82 cm.	3.5 cm.	.8 cm.	7.
				180°	105.5				.85	7.8
				45°	108				.9	10.9
		Blue-green	98	315°	96.2	+ 7.4	+7.7	4	.6	71
				180°	90.6				.8	7.2
				45°	88.5				.9	6.15
16.6 cp. standard lamp	67 cp. standard lamp, 89 cm. distant from photometric screen	Red	86	315°	96.5	−15	−6.5	3	.8	9
				180°	101				.85	11.8
				45°	103				.8	11.4
		Blue-green	84.3	315°	78.5	+10.8	+8	4.3	.9	5.3
				180°	73.5				.85	7.4
				45°	70.5				.88	7

of the blue-green. (3) The amount of change in the photometric value of the color produced by varying the ratio of exposure to colored and colorless light was many times the smallest amount of change that can be detected by the method of flicker, and, therefore, must be considered of consequence in relation to the application of the method to practical work.

Column 1 of these tables represents the source of white light; Column 2, the source of colored light; Column 3, the color used; Column 4, the distance of the white light from the disc when judgment of equality is given by equality of brightness method; Column 5, the value of the colored sector for the method of flicker; Column 6, the distance from the disc at which the white light has to be placed to give the judgment of no flicker; Column 7, the difference in the distance the white light was placed for the equality of brightness method and the flicker method with 180° of colored sector; Column 8, the change in the distance of the white light produced by varying the value of the colored sectors in the method of flicker; Column 9, the distance the white light has to be moved in the equality of brightness method to change the judgment from equality to just noticeably lighter or darker; Column 10, the distance the white light has to be moved in the flicker method to change the judgment from no flicker to just noticeable flicker; and Column 11, the number of revolutions per second of the sectored disc for the method of flicker.

Tables IV. and V. represent the results of Tables II. and III. expressed in percentage of luminosity at the photometric screen.

Pigment papers are still used in a great many laboratories for the investigation of color sensitivity, and because of their convenience and ease of manipulation, they probably will be used for many years to come for preliminary work and for a certain class of investigations in which only comparative results are wanted. In estimating the brightness or luminosity of these pigment colors, the method of flicker is now much more extensively used perhaps than any of the other methods of making brightness comparisons. For this reason we have considered it worth while to extend our work to the

Table IV

Observer *A*

Showing the Results in Table II. Expressed in Percentage of Luminosity

Source of White Light	Source of Colored Light	Color	Disagreement Between Equality of Brightness Method and Flicker Method with 180° Open Sector	Change Produced by Varying Sectors	Amount of Change that Can Be Detected by: Equality of Brightness Method	Amount of Change that Can Be Detected by: Flicker Method
13 cp.	13 cp. 151 cm. distant from photometric screen	Red	−15 %	− 4.8%	5 %	.4%
		Blue-green	+12.3	+ 6.3	3.7	.6
	52 cp. 151 cm. distant from photometric screen	Red	−20	− 7.5	7	.4
		Blue-green	+30	+13	7.3	.6
	130 cp. 89 cm. distant from photometric screen	Red	−21	− 9	7	.9
		Blue-green	+19.7	+ 7.3	6.8	.7
16.6 cp. standard lamp	67 cp. standard lamp, 89 cm. distant from photometric screen	Red	−23.6	− 8.3	8.7	1
		Blue-green	+33	+ 8.3	8.5	.8

Table V

Observer *B*

13 cp.	52 cp. 151 cm. distant from photometric screen	Red	−30%	−16%	7.5%	1.7%
		Blue-green	+17.	+18	7.7	1.2
16.6 cp. standard lamp	67 cp. standard lamp, 89 cm. distant from photometric screen	Red	−28.	−12.4	6.5	1.6
		Blue-green	+31.7	+24.	9	2

investigation of the effect of varying the value of the colored and the colorless sectors on the brightness of the pigment colors as determined by the method of flicker. Of the devices available for applying the method to these colors, the Schenck apparatus was selected as best suited to our purpose. As colors to be investigated, the red, green, blue, and yellow of the Hering series of standard papers were chosen. Sectors of the value of 180°, 270°, and 300° were used. Values lower

than 180° were not used because they could not be accurately obtained with the type of photometer employed. Two intensities of illumination were used, one of 390 foot-candles (vertical component) received directly under a skylight and diffusion sash of ground glass; the other, 5 foot-candles, the illumination of a room lighted by windows. Space will be given here only for the results for the higher illumination. This illumination was carefully chosen far above the range of intensities at which the Purkinje phenomemon occurs when the eye is fully exposed to its stimulus, in order to subject our demonstration to a rigid test. We were seeking, for example, to ascertain whether an intensity might not be found so high that the underexposure of the eye to its stimulus by the method of flicker would not cause an underestimation of the brightness of red and yellow and an overestimation of the brightness of blue and green.[1] That these underestimations and overestimations occur at this high illumination and by amounts many times the smallest brightness difference that can be detected by the method, will be shown in Table VI.

Column 1 of this table shows the color used; Column 2, the black-white value of the color estimated by the equality of brightness method; Column 3 gives the value of the colored sector; Column 4, the white-black value of the color estimated by the flicker method; Column 5 gives the difference in the result by the equality of brightness and flicker method with 180° colored sector; Column 6 gives the change produced in the result by the method of flicker by varying the size of the colored sector; Column 7 gives the amount of change that can be detected by the equality of brightness method; and Column 8, by the flicker method.

III. The Method of Flicker Does not Give Results Which Agree in the Average with those Obtained by the Equality of Brightness Method

Nothing will be added in this section except to make our comparisons at the intensity of illumination found to be most

[1] We have been careful to choose high intensities because Dr. Ives has contended that at high intensities the disagreement between the methods of flicker and equality of brightness tends to disappear.

Table VI

Observer *A*

Showing that the Underestimation of Red and Yellow and the Overestimation of Blue and Green is a Characteristic of the Method of Flicker for Light of the Intensity Used in this Work, and that the Amount of this Underestimation and Overestimation is a Variable Function of the Ratio of the Time of Exposure of the Eye to the Colored and the Colorless Light.

Color	Equality of Brightness Method	Flicker Method		Difference by Equality of Brightness Method and by Flicker Method with 180° Colored Sector	Change Produced by Varying Sectors	Amount of Change that can be Detected by	
	White-black Value	Value of Colored Sector	White-black Value			Equality of Brightness Method	Flicker Method
Red	White 64° Black 296°	300°	White 58.9° Black 301.1°	−17.4°	−12.3°	8°	1.8°
		270°	White 56.2° Black 303.8°				1.2°
		180°	White 46.6° Black 313.4°				1.8°
Yellow	White 332° Black 28°	300°	White 328.3° Black 31.7°	−18.6°	−14.9°	9.5°	2°
		270°	White 321.7° Black 38.3°				1.8°
		180°	White 313.4° Black 46.6°				1.8°
Green	White 88.5° Black 251.5°	300°	White 99° Black 261°	+26.4°	+15.9°	9°	.45°
		270°	White 105.5° Black 254.5°				.9°
		180°	White 114.9° Black 245.1°				.45°
Blue	White 12.5° Black 347.5°	300°	White 14.5° Black 345.5°	+10.7°	+8.7°	5.3°	2.2°
		270°	White 19.1° Black 340.9°				1.4°
		180°	White 23.2° Black 336.8°				.9°

avorable for agreement by Dr. Ives.[1] The plan of the apparatus used in this work is indicated in Fig. 6. A spectrocope was used to give the colored light; a 32-cp. carbon amp (*F*) was used as the source of the colorless light. This amp gave a light of the same quality as that used by Dr. Ives, amely, the quality of the carbon standard of 4.85 watts per nean spherical candle. When placed at 32.6 cm. from the ectored disc (*D*), 270 meter candles of light were reflected

[1] Ives, H. E., *op. cit.*, p. 173.

from the disc. The eye piece was removed from the spectroscope and a lens system was used in its place consisting of two lenses (A) and (B), one to render the light emerging from the objective slit (C) parallel, and the other to focus it on the eye 30 cm. distant. Between the eye and the focusing lens (B) was interposed the sectored disc (D). Thus the light reflected from the sectored disc suffered no absorption in passing to the eye. A stimulus-opening (E) 16 mm. in diameter was placed in front of the disc 20 cm. from the eye. This subtended the

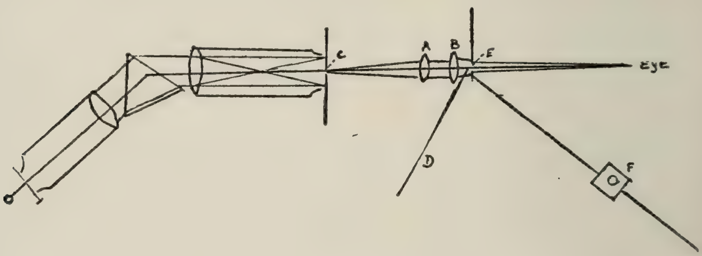

FIG. 6

same visual angle as the field size that Dr. Ives found to be the most favorable. A pupillary aperture 1 mm. square placed in front of the eye reduced the light reflected from the white disc to the intensity called by Dr. Ives 270 illumination units.[1] The colors used were a very narrow band of the spectrum in the region of .68 μ, .57 μ, .52 μ, and .47 μ, giving the four pure colors red, yellow, green, and blue. The method of making the comparison was as follows: The sectored disc was turned so that its edge bisected horizontally the photometric field, and the luminosity of the colored field was altered by changing the width of the collimator-slit until it equalled by the equality of brightness method the 270 illumination units. Using this slit width, then, the disc was rotated and the position of the white light was adjusted until no

[1] By using a pupillary aperture 1 mm. square, Dr. Ives has reduced the light entering the eye by an amount which, so far as we can see, can not be determined. He has established an arbitrary unit which he calls an illumination unit. We can not, therefore, compare the intensities of light used by us in the preceding experiments (pp. 134 ff.) with the 270 illumination units used by Dr. Ives. If one were to judge, however, by the apparent brightness of the disc in the two cases, he would have to say that the amount of light entering the eye was considerably greater for our

flicker was obtained. The flicker determinations were made with 315°, 180°, and 45° total open sector as before. The results are shown in Tables VII and VIII.

Table VII

Observer *A*

Showing that the Underestimation of Red and Yellow and the Overestimation of Blue and Green is a Characteristic of the Method of Flicker for Lights of the Intensity Used in this Work, and that the Amount of this Underestimation and Overestimation is a Variable Function of the Ratio of the Time of Exposure of the Eye to the Colored and the Colorless Light. Intensity same as was used by Ives

Wave-length	Equality of Brightness Method: Distance of White Light Giving Equality of Illumination	Flicker Method: Value of Colored Sector	Flicker Method: Distance of White Light Giving no Flicker	Difference by Equality of Brightness Method and by Flicker Method with 180° Colored Sector	Change Produced by Varying Sectors	Amount of Change that Can Be Detected by: Equality of Brightness Method	Amount of Change that Can Be Detected by: Flicker Method	No. of Revolutions per Second, Flicker Method
.68 μ	32.6 cm.	315°	41.5 cm.	−11.6 cm.	−3.6 cm.	2.4 cm.	.5 cm.	9.2
		180°	44.2				.45	12
		45°	45.1				.5	11
.57 μ	32.6	315°	37.4	− 6.9	−3.4	2.8	.4	9.8
		180°	39.5				.4	14
		45°	40.8				.4	12
.52 μ	32.6	315°	23	+13.6	+4.9	2	.5	9.7
		180°	19				.4	13
		45°	18.1				.4	11.7
.47 μ	32.6	315°	23	+13.8	+5	2.3	.45	9.9
		180°	18.8				.4	14.1
		45°	18				.45	12

higher intensities than the 270 illumination units used by Dr. Ives. Thus it seems probable that most of our preceding tests were made with an intensity of light equal to or greater than that used by him. His claim, it will be remembered, was that one of the two causes of disagreement between the results obtained by the methods of flicker and equality of brightness in preceding experiments is the low intensity of the lights used. (The other was the lack of proper regulation of the size of the photometric field.) We do not believe that either one of these factors is the fundamental cause of disagreement, as is attested in our experiments by the fact that strong disagreement remains when both of them have been eliminated, at least, as completely as they were eliminated by Dr. Ives. A consideration of the functioning of the eye under very short exposures to light, shows, we believe, a much more fundamental cause of disagreement, namely, the difference in the way in which the eye responds to light stimuli when presented for the lengths of time used in the two methods.

TABLE VIII

OBSERVER *B*

.68 μ	32.6	315°	41.3	−11.6	−4	3	.8	12
		180°	44.2				.7	14
		45°	45.3				.8	13.4
.57 μ	32.6	315°	38	− 8.9	−4.3	2.9	.9	12.5
		180°	41.5				.6	14.2
		45°	42.3				.8	13.1
.52 μ	32.6	315°	23.4	+12.1	+3.9	3.3	.8	12
		180°	20.5				.7	14
		45°	19.5				.7	12.2
.47 μ	32.6	315°	22.8	+12.6	+4	3.5	.9	11.1
		180°	20				.7	14.4
		45°	18.8				.8	12.8

It was stated in the beginning of the paper that disagreement between the results of the method of flicker and equality of brightness would be shown from a preponderance of the work done by others who have made the comparison. As a general case the fact scarcely needs more than the pointing out. Before the work of Ives, disagreement was pretty generally admitted. Bell[1] says: "That the flicker and equality of brightness methods do not give coincident results when we consider the general case of flicker photometers, as compared with equality of brightness photometers, is a fact that has been too long familiar to photometrists to admit of a discussion." Comparisons of the two methods have been made by Whitman, Wilde, Dow, Bell, Stuhr, Luckiesh and Ives. Whitman[2] compared the luminosities of a red and green light placed 6 ft. apart on a photometer bar. He found that the setting of the photometer for equality of illumination differed for the equality of brightness and flicker methods by 1.2 ft. for one observer, and .8 ft. for another. Wilde[3] photometered a tungsten lamp against a carbon by the methods of flicker and equality of brightness, and found a difference of 6 per cent. in the result. Bell[4] compared the ratio of lumin-

[1] Bell, L., 'Acuity in Monochromatic Light,' *Electrical World*, Sept. 9, 1911, *58*, p. 637.

[2] Whitman, F. P., 'On the Photometry of Differently Colored Lights and the Flicker Photometer,' *Physical Review*, 1896, *3*, pp. 241-249.

[3] Wilde, L. W., 'The Photometry of Differently Colored Lights,' *The Electrician*, July 16, 1909, *63*, pp. 540-541.

[4] Bell, L., 'Chromatic Aberration and Visual Acuity,' *Electrical World*, May 11, 1911, *57*, pp. 1163-1166.

osities of a mercury vapor lamp with that of a tungsten lamp by means of the flicker method and found it to be 5.42. These same lights by the equality of brightness method gave a ratio ranging from 6.86 to 10.93 for different observers. Stuhr[1] compared red and green lights by several methods including the method of flicker and equality of brightness. He found that the mean deviation of the values obtained by the method of flicker from those obtained by the equality of brightness method amounted to 14.14 per cent. Luckiesh[2] photometered a red against a blue-green light by the methods of flicker and equality of brightness, and found a difference of 62 per cent. in the ratios of the luminosities of the two lights by the two methods.

Two factors have in the main been assigned to the cause of the disagreement: the effect of intensity and of size of the photometric field. Lauriol, Dow, Millar, Ives, and Luckiesh have investigated the former factor, and Schenck, Dow, and Ives the latter. These are both factors which affect the results of both methods. In comparison little attempt has been made to find the factors that affect the results of each method alone. As a general case these, it would seem, might be more apt to prove a source of disagreement than those which affect both methods.

With regard to the intensity of the light as a factor, Lauriol[3] and Dow[4] claim that the relative shift in the brightness of the different colors at low illuminations is shown by both methods. The shift for Dow, however, is more pronounced in the equality of brightness than the flicker determinations. For Lauriol the shift for the different colors varies in magnitude by the two methods and in some cases in direction. Millar,[5] on the other hand, claims that the

[1] Stuhr, J., 'Ueber die Bestimmung des Aequivalenzwertes verschiedenfarbiger Lichtquellen,' Kiel, Philos. Diss., Vol. *19*, Okt., 1908, p. 50.

[2] Luckiesh, M., 'Purkinje Effect and Comparison of Flicker and Equality of Brightness Photometers,' *Electrical World*, March 22, 1913, p. 620.

[3] Lauriol, 'Le photomètre à papillotement et la photométrie heterochrome,' *Bull. Soc. Intern. des Électriciens*, 1904, pp. 647–652.

[4] Dow, J. S., 'Color Phenomena in Photometry,' *Philos. Mag.*, 1906, *12*, Ser. 6, p. 131.

[5] Millar, P. S., 'The Problem of Heterochromatic Photometry,' *Trans. Illuminating Engineering Society*, 1909, *4*, p. 769.

Purkinje phenomenon is not shown at all by the flicke method at low illuminations, while Ives[1] and Luckiesh[2] g to the other extreme and declare that a reverse Purkinj effect is obtained by the flicker method. With regard to siz of field as a factor, Schenck[3] found that a decrease in siz lowered the mean variation for the flicker method and de creased the luminosity value obtained for all the colors Dow[4] found that as the size of the field was decreased, rec and yellow lightened relatively to green and blue. Thi effect was more pronounced for the equality of brightnes than for the flicker method. Ives[5] found this effect for th equality of brightness method, but the reverse effect for th flicker method.

Ives, admitting the disagreement between the tw methods and accepting size of field and intensity of th stimulus as the cause of the disagreement, sought to determin whether a field size and intensity could not be found fo which the two methods agree. He photometered different portions of the spectrum against carbon lamps at a number o intensities and with a number of field sizes. He found in general for five observers that the luminosity curves obtained by each method differed. This difference, however, was less for high intensities than for low.

A table is appended (Table IX) in which is shown in percentage the difference in results gotten by the five observers used by Dr. Ives at the intensity of light which he calls most favorable to agreement for the two methods (250 Illumination Units). It will be seen that the disagreement for these observers is in the average as great, if not greater than was gotten by our own observers. Percentage of overestimation by the method of flicker is designated by +, and underestimation by −.

[1] Ives, H. E., *op. cit.*, p. 171.

[2] Luckiesh, M., *op. cit.*, p. 620.

[3] Schenck, F., 'Ueber die Bestimmung der Helligkeit grauer und farbiger Pigmentpapiere mittels intermittirende Netzhautreizung,' *Pflüger's Archiv*, 1896, *64*, pp. 607–628.

[4] Dow, J. S., *op. cit.*, pp. 130–134; 'Physiological Principles Underlying the Flicker Photometer,' *Philos. Mag.*, 1910, *19*, Ser. 6, pp. 58–77.

[5] Ives, H. E., *op. cit.*, p. 172.

Table IX

Showing in percentage the difference in results between the methods of flicker and equality of brightness for the five observers used by Dr. Ives at the intensity of light which he calls most favorable.

λ	H. E. I.	M. L.	P. W. C.	C. F. L.	F. E. C.
.653μ	−12. %	+29. %	−18. %	−51. %	−50. %
.643μ	− 3.6	+56.	− 7.0	−31.	−23.7
.632μ	− 4.3	+20.	−15.5	−45.5	−12.9
.622μ	− 7.3	+12.5	− 4.2	−42.	−15.9
.612μ	−10.	+ 8.3	− 6.5	− 7.5	+ 0.3
.594μ	− 1.	− 0.5	− 0.5	+ 7.5	+ 5.8
.574μ	+ 0.5	− 2.4	− 2.5	+27.	− 5.9
.555μ	− 0.4	− 8.0	−11.9	− 4.8	+ 8.9
.545μ	− 3.1	− 8.4	−13.8	+ 3.	+ 8.
.536μ	− 1.9	− 4.0	−12.6	−12.	+14.3
.526μ	0	− 8.7	−21.4	− 3.	+33.5
.517μ	+ 0.6	−10.8	−13.8	−33.	+30.0

It has been our purpose in general in this part of the paper to indicate a field of investigation in the department of physiological optics about which little is known as yet with certainty, rather than to report a finished piece of work or to attempt to draw positive conclusions. When functioning under the conditions imposed by the method of flicker, too little is known of the characteristics of the eye, we believe, to render safe its use as a measuring instrument. Our purpose in particular has been to point out and show the effect of a factor which we believe to be an important source of disagreement between the equality of brightness and the flicker methods, and to suggest that a more careful study be made of the factors that influence the method of flicker before it is adopted in its present form as the method for the standardizing laboratories. Just as one factor has been overlooked, so there may be others the influence of which should not be ignored.

Appendix

Three other points which may be of interest in connection with the above work are appended here. The first two were discussed by Dr. Ives in a series of articles on the method of flicker in the *Philos. Mag.*, 1912, *24*, Ser. 6, pp. 149–188, 352–370, 744–751, 845–853, 853–863. (1) In the third of his series of articles, he apparently wishes to show that the cause

of the disagreement between the results of the methods of flicker and equality of brightness lies on the side of the latter method. That is, the difficulty of making the judgment is so great that not an equalization, only an 'appraisement' is accomplished. To demonstrate this, he attempts to get rid of the disturbing factor of color difference in the equality of brightness method by making his comparisons always between lights differing only slightly in composition. That is, a green is compared with a green slightly shifted toward the yellow or blue, etc. (See his work with the 'cascade' method, p. 748.) A curve of luminosity for the spectrum obtained in this way is found to agree more closely with the flicker curve than one obtained in the ordinary way. The following things may be said of this demonstration, however. In the first place, he states that the cumulative errors are so great in the method that he could not begin at one point in the spectrum having a given luminosity and work in a given direction, then reverse this direction of working and obtain at all a close approximation to the luminosity value for the point at which he started. For this reason he drops the point by point procedure of the 'cascade' method, and plots his curve by taking his observations at twelve points in the spectrum. From the observations of these points the whole curve is constructed. In the second place, his method does not entirely accomplish his purpose of getting rid of all difference in color quality between the lights compared. In order to add some further data bearing upon the question whether the lack of agreement hitherto found between the results obtained by the equality of brightness and flicker methods could have been due to the difficulty of making the equality of brightness judgments of fields differing in color quality, we have thought it worth while to make the comparison using an equality of brightness method which for the purposes of this investigation presents, we believe, some points of advantage over the method used by Dr. Ives.[1] That is,

[1] We do not, however, mean to propose this as an entirely satisfactory method of heterochromatic photometry for the reason given in the discussion of the relation of the method to the Talbot-Plateau law (see footnote p. 149). We are using the method here merely to show that when the disturbing factor of color difference in the

the method we have used offers even less chances for errors in judgment, is simpler, and entirely eliminates the presence of a second color in the fields to be compared. The method is as follows: The sectored disc was adjusted so that its outer edge bisected vertically the photometric field. A standard colorless light was moved to the position on the photometer bar that gave the judgment of equality by the method of flicker, and the disc was rotated at the fusion rate. Half of the field was thus of color of the original saturation and luminosity, and the other half was a fusion of the colored sector of the original saturation and luminosity and a gray sector of the luminosity of the color as determined by the method of flicker. Now, if the luminosity of the color by the method of flicker were the same as by the equality of brightness method, the two halves of the photometric field should match in luminosity (within the limits imposed by the Talbot-Plateau law).[1] That is, the addition of the colorless

fields to be compared is eliminated from the equality of brightness method, there is still a large, in fact an apparently undiminished characteristic difference between the results of the equality of brightness and flicker methods, which, so far as one can see, can in no way be ascribed to the equality of brightness method employed. The degree to which the influence of color difference on the judgment of the brightness equality of the fields compared is removed by this method is shown by the greatly increased reproducibility of the judgment. For our observers, the reproducibility is almost as great as it was for the method of flicker. There was thus but little more of the element of appraisement in this method than there was in the method of flicker, while the characteristic difference in the results obtained by the two methods was not, so far as could be determined, appreciably lessened.

[1] A few words are needed to explain what is meant above by "within the limits imposed by the Talbot-Plateau law." It could scarcely be expected from a consideration of this law that the two fields would match especially under the dark-room conditions under which photometry is done, even when the gray sector was chosen equal in brightness to the color by the equality of brightness method. That is, when the colored is mixed with the gray sector by the method of successive impressions, there is a reduction of the intensity of each impression which is the same as would be gotten were the intensity of each light to be reduced in proportion to the time of exposure of the eye to each light to the total time of exposure of the eye to both lights. (See the discussion of the Talbot-Plateau law, p. 121.) That is, if the value of each sector is 180°, the impression made upon the eye by each light is the same, according to the Talbot-Plateau law, as if both lights were reduced one-half in intensity. But in suffering the reduction, the luminosity of the colored sector is not changed the same in amount as is that of the gray sector. If it is blue or green, for example, its brightness is not reduced so much as is that of the gray sector, and its fusion with the gray sector tends to lighten that sector and to make the second half of the field lighter than

to the colored sector would produce no change in its luminosity, and the two halves of the field would present a fully saturated color of a given luminosity and a less saturated color of the same luminosity (within the limits imposed above). But if there were an underestimation or an overestimation o the luminosity of the color by the method of flicker, th brightness of the second half of the field would be modifie in this direction in proportion to the value of the colored an colorless sector; and if the underestimation or overestimatio were great enough the two halves would not match. I proportion as the colorless sector is made larger in the secon half of the field, the color of the mixture loses saturation, an the comparison with the fully saturated half of the field becomes more difficult to make. On the other hand, i proportion as the colored sector is made larger, the effect o the brightness of the mixture of the difference between th flicker value and the true sensation value, if such a differen exists, is lost. After considerable preliminary investigatic it was decided to use in turn colored sectors of the value 300°, 270°, and 180°. The comparison was made for ligh of the intensities specified in the preceding sections of th paper. In all cases when the color was red or yellow, th

the first. If, however, the colored sector is red or yellow, it is reduced more in brig ness than is the gray sector, and its fusion with that sector tends to darken it and to render the second half of the photometric field darker than the first. We ha conducted experiments to determine whether the above effect, which is a direct co lary of the Talbot-Plateau law, actually takes place in observable amounts. Wh the light of the spectrum or light of the purity given by the Wratten and Wainwri filters was used, we found that it did. That is, when the second half of the field w green or blue and was fused with a gray of the luminosity of the color employ determined by the equality of brightness method, this half of the field was observa lighter than the first half. Conversely, when red or yellow was used, the second l of the field was darker than the first. The effect, however, was not nearly so grea it was when the gray sector was made of the brightness of the color as determi by the method of flicker. That is, if two experiments are conducted, one in wh the second half of the field is made by fusing the colored sector with a gray sec of the brightness of the color as determined by the equality of brightness method, the other in which this half of the field is made by fusing the colored sector with a g sector of the brightness of the color as determined by the method of flicker, the dif ence in brightness between the two halves of the field is quite appreciably gre in the second case than in the first. For example, when the colors are green and bl the second half of the field is more too light in the second case than in the first; a when red and yellow, it is more too dark.

second half of the field was darker than the first; and when either blue or green, was lighter than the first half of the field. Determinations were made also of how much the colorless light had to be moved to make the two halves of the field match. These distances were not much different from those contained in the tables in the preceding sections of the paper expressing the difference in the estimation of the luminosity of the colors by the methods of flicker and equality of brightness (see pp. 136, 137),—certainly not any more than should be expected when it is remembered that a part of the effect of the difference is lost by mixing the colorless light representing the flicker determination with a sector of the colored light in its true luminosity value. The work was done also with pigment papers with a similar result. Thus it seems reasonable to conclude that the cause of the disagreement between the two methods can not be attributed entirely at least to the difficulty of making the equality of brightness judgment due to the difference in color quality between the fields compared, for in the above cases the color quality of the lights compared was the same. In the third place, disregarding the results of the above experiments, the writers scarcely need point out that it would be extremely difficult to explain such a systematic drift of luminosity in one direction in one part of the spectrum, and in the opposite direction in the other part, as we obtained, in terms of errors due to a false judgment of the sensations actually aroused. Moreover, it would be just as difficult to explain Dr. Ives's own reverse Purkinje effect in terms of a false judgment of the actual brightness values presented in sensation; or the closer agreement he obtains between the results by the methods of flicker and equality of brightness at high illuminations, in which case there is the maximum amount of color present and, therefore, the maximum color difference to disturb the equality of brightness judgment between colored and colorless light. Moreover, the kind of errors that one finds as due to uncertainty of judgment is a deviation on either side of a mean. This occurs when all other factors are eliminated if several judgments of the same sensation are made. Such

errors are compensated for by taking the average or mean c the determinations. If it is not conceded that they are con pensated for, how, for example, can the average of the resul by the equality of brightness method be taken as a standar in terms of which to evaluate the results obtained by oth methods? (See Whitman, Schenck, Wilde, etc.).[1] Surel this should not be allowed if there were a consistent deviatic in any one direction from the true brightness value for a give color due to errors in judgment. Moreover, such a characte istic drift due to errors in judgment is unknown in all previo work in psychophysics, and not only unknown, but unsu pected.

(2) In the fourth paper of the series,[2] Dr. Ives applies a test to the method of flicker what he calls two axioms measurement. These are (*a*) things which are equal to t same things shall be equal to each other; and (*b*) the wh shall be equal to the sum of its parts. He finds that t method of flicker satisfies these axioms better than the equa- ty of brightness method. We would point out that the tests would not be expected to reveal to any considerable c- gree the influence of the factor we are discussing. They a tests which would apply as a check on the power to make t judgment of the brightness of the sensation properly, or any tendency of this brightness equality to drift in one dir- tion in any part of the spectrum without a compensating dr t in the opposite direction in some other part of the spectru ; but they are not tests that could be expected to show wheth r or not there is underestimation in one half of the spectrun and overestimation in the other half. For example, the a a of the curve of the spectrum plotted by the method of flick r might very well sum up to the value of the reassembled wh e light because of the compensating effect of the underest- mation of one half of the spectrum and the overestimation f the other half.

(3) Since the foregoing paper was presented, the writ s

[1] While Dr. Ives does not explicitly state that he takes the equality of bright ss method as a standard in terms of which to evaluate the correctness of the result y other methods, the point of view is strongly implied in his first paper (*loc. cit.*).

[2] *Philos. Mag.*, 1912, *24*, Ser. *6*, pp. 845–853.

have met with the contention from a prominent advocate of the method of flicker that the effect of a reduction of intensity is not given by the method of flicker because each individual impression is carried over until the next is given, with sufficient intensity to preclude the effect of reduction. Whether or not each individual impression can be considered as carrying over with sufficient intensity to preclude the effect of reduction is an important point and should, lest the issue be in doubt, be included in a discussion of the principles underlying the method of flicker. It may not be out of place, therefore, for us to consider the question here briefly, even though it has not as yet, so far as we know, been discussed in print.

As evidence that each individual impression should be considered as carrying over with sufficient intensity to preclude the effect of reduction, it was contended, as the case was presented to us, that the rate used in the method of flicker is the fusion rate of the two impressions. Two reasons were given for considering this rate as the fusion rate. (1) If the two impressions be red and green, for example, yellow is produced at the rate of succession used in the flicker method. Yellow, it was pointed out, is a fusion of red and green, and, therefore, the rate used must be considered as the fusion rate for these colors. In answer to this point we would again call attention to the phenomena (see p. 116) which are produced in sensation when two impressions differing in color and brightness are given to the eye successively at different rates of speed.[1] When the rate is very slow, the effect of separate and distinct impressions is given, each in its proper color and brightness. When a little faster rate is used, the impressions become confused and a flickering effect is produced both in the color and brightness components of the sensation. When the rate is made still faster, the flickering of color dies out, leaving only brightness flicker; that is, the color components of the two sensations have been fused. That the brightness

[1] We wish at this point to state very emphatically that our account of the fusion of the color and brightness components of sensation at different rates of speed is not based on any theoretical conception of a separate brightness and color sense, but upon actual observation of the phenomena that take place when light impressions differing in color and luminosity are combined at different rates of succession. These phe-

components have not been fused, however, is attested by the presence of brightness flicker, which is now left outstanding in a field uniform as to color quality. As the rate of succession is made still faster, brightness flicker becomes less and less pronounced and finally disappears.[1] The rate at which this disappearance takes place is the fusion rate for the brightness components for the two sensations, and is much higher for all the colors than is the rate at which the fusion of the color components takes place.[2] (Interpreted in terms of the

nomena may be readily demonstrated by any kind of flicker photometer head if a sufficiently sensitive control of speed of rotation is had. (We have used for the control of speed of rotation a rheostat and motor especially constructed to give fine changes.) It can be very plainly and perhaps most conveniently demonstrated by rotating sectors of pigment papers at the proper gradations of speed in a good daylight illumination.

[1] We find that Krüss (*Physical. Zeitschr.*, 1904, *5*, p. 67) gives a description o the phenomena that take place in sensation when two impressions differing in colo and brightness are given to the eye successively at different rates of speed, very similar to that we have given here. He says: "If we slowly alternate the illuminatio from two differently colored light sources, for example, from a Hefner lamp and a ga burner, we clearly distinguish a succession of reddish and bluish bands with weal washed-out limits between them. As the rate of succession is increased it become progressively more difficult to distinguish the two colors from each other. At a comparatively low rate they begin to lose themselves in each other. At a slightly highe rate the difference in color disappears altogether and we have a color mixture. In thi mixture, however, a brightness succession, a flicker, is observable which disappear only by a further increase in the rate of succession. Physiologically, it is of grea interest that the distinguishing of separate colors ceases at a much slower rate c succession than the rate at which completely continuous sensation begins."

[2] The following values will serve to give a rough comparative showing of th rates at which the phenomena described above take place. The colors used were re and green. They were obtained from pigment papers of the Hering series of standar papers and from gelatine filters. Two intensities of color were employed in each cas The brightness of the Hering green for the lower intensity of illumination was .00081 cp. per sq. in.; of the red, .000594 cp. per sq. in. The phenomenon of separat impressions occurred from the lowest speed up to 6.9 revolutions per second. Th impression of an intermingled color and brightness flicker was given from this ra up to 9.6 revolutions per second, at which rate the color components of the sensatic fused, giving a field uniform as to color quality but with a strong outstanding brightne flicker. Brightness flicker was present until a speed of 22 revolutions per second w obtained. At this speed the brightness components in sensation were complete fused and the rotating disc presented a surface uniform both as to color and brightnes In making these determinations, the same sized field was used as was employed in o work with the method of flicker, *i. e.*, the disc was viewed through an aperture 3 mı $\times$ 3 mm. in a gray screen (Hering No. 24) 20 cm. from the eye. For the higher inte sity the green surface was illuminated to a brightness of .00242 cp. per sq. in.; t

duration of the impression after the light has been cut off, this means, of course, that the brightness component in the sensation does not carry over under these conditions with as little loss of intensity as does the color component.) It is evident, then, that the rate of succession which is used in the method of flicker is at or near the fusion rate for the color components of the two sensations, not for the brightness components; nor is it anywhere near the fusion rate for the brightness components. But it is the brightness components in which we are interested in photometry. That is, it is in terms of the brightness component that all photometric judgments are made. The color components, when they differ in tone, only serve to confuse the judgment. It is, therefore, our object in all methods of photometry as much as possible to get rid of difference in the color components. This can be accomplished in the method of flicker only because of the fact we have just pointed out, namely, that the fusion of the color component in sensation comes at a much lower rate of succession than the fusion of the brightness component. That is, all color differences, whether sensed as distinct or as flickering sensations, disappear at a rate of succession that has little or no effect on eliminating the brightness factor, or in this case the equivalent of this elimination, the fusion of the brightness components of the two sensations. In fact, if there were no difference in the fusion rate of the color and brightness components, the flickering color impressions would so mask the presence of brightness flicker at any rate of succession that could be used, that the method would doubtless

red, .00167 cp. per sq. in. The phenomenon of separate impressions occurred from the lowest speed to 6 revolutions per second, at which rate color flicker began. Color fusion took place at 12.4 revolutions per second, and brightness fusion at 29.3 revolutions per second. At the lower intensity for the filters, the brightness of the green was .154 cp. per sq. in.; for the red, .099 cp. per sq. in. As compared with their brightness these colors were much more poorly saturated than were the Hering pigments. The phenomenon of separate impressions ceased and color flicker began at 6.5 per second. Color fusion took place at 11.5 revolutions per second, and brightness fusion took place at 35.4 revolutions per second. At the higher intensity for the filters the brightness of the green was .22 cp. per sq. in.; for the red, .143 cp. per sq. in. Color flicker began at 7 revolutions per second; color fusion took place at 12.9 revolutions per second; and brightness fusion was complete at 38.3 revolutions per second.

have little if any greater sensitivity than the equality o brightness method. (2) The second point that was citec in support of the contention that the rate used in the methoc of flicker is the fusion rate for the two sensations aroused, i that no brightness flicker is present when in terms of th method the two impressions are adjudged of the same bright ness. This to the present writers seems indeed a strang confusion of meanings. Fusion is a term used to represen what takes place when two impressions or sensations differin in quality are combined into one, the same or homogeneou as to quality. This combination may be obtained in case c light stimuli, for example, by mixing two lights evenly an allowing them to act simultaneously on the eye; or it may b obtained by giving two lights to the eye in succession at suc a rate that the sensation aroused by the one lasts over unt the next one is set up with a sufficient degree of intensity t give the effect of continuity or homogeneity of quality. I may add to the clearness of our discussion, then, to conside what takes place in this regard when two impressions differin in brightness are given to the eye at the different rates c succession mentioned in the preceding paragraph. At th rate at which distinct and separate impressions are give each sensation obviously dies away completely before th next one is aroused. If a rate slightly faster than this selected, the sensation does not die away completely befo the next one is set up.

There is a slight lasting-over from one impression to th next. This when the two impressions differ in brightne gives the effect of a wavering or flickering sensation. At th lowest speed at which flicker is produced, the effect of th lasting-over has its minimum value. As the speed is furth increased it becomes greater and attains its maximum val at the rate of complete brightness fusion.[1] (See discussion Talbot-Plateau law, pp. 121.) It is obvious, then, that th rate of speed employed in the method of flicker, which roughly speaking, the lowest rate at which brightness flick

[1] At the fusion rate neither sensation rises to its maximum value, for example, n has a chance to die away until the next one develops. The effect is that of a c tinuous sensation homogeneous as to color and brightness.

can be obtained unmixed with color flicker, is not the fusion rate for the brightness components in sensation nor is it anywhere near this rate.[1] It is equally obvious also that the absence of flicker when the final adjustment of the lights has been made for a photometric balance, can not be adduced as any evidence that this rate is the fusion rate for the brightness component of the two sensations, or, what is more significant in relation to the above mentioned claim, that it is a rate to which more than a minimum of lasting-over effect from impression to impression can be ascribed. Flicker is absent merely because, in accord with the purpose of the method, such an adjustment of the distance of the lights from the photometer head is made that the sensations aroused by the two lights are of equal brightness. Such sensations do not flicker whatever may be their rate of succession. It can, therefore, be considered as little more than absurd to adduce the absence of flicker when the photometric balance has been attained as evidence that the rate used is the fusion rate for the brightness components of sensation, and to pass from this to the conclusion that the same amount or anywhere near the same amount of carrying-over effect is present for this rate as obtains when the fusion rate is used. In fact, if this carrying-over effect were present to any considerable degree, the whole point of the flicker method would be lost. That is, it is the purpose in the method of flicker to select a rate of succession that will give the eye the maximum of sensitivity to brightness difference (or flicker), namely, the lowest rate at which flicker can be produced, rather than a rate that will fuse out this difference in sensation.

But supposing it could be established, as was contended, that we have in the rate used in the method of flicker a complete color and brightness fusion of the sensations aroused by the two lights, little would be gained for the claim that there is no reduction in the effect on sensation of the two lights employed, if it be granted, for example, that the Talbot-Plateau law is true. In substance this law is as

[1] Flicker and fusion are in fact antithetical terms, and the rates of succession which are favorable for each are widely separated in the scale of frequencies.

follows. When once the rate of rotation is sufficient to gi a uniform sensation, the color and brightness of the disc a the same as they would be if all the light reflected from t sectors were evenly distributed over the surface of the dis and no further increase in rapidity produces any effect on i appearance.[1] In terms of this law it is seen that the effect o

[1] See H. F. Talbot, 'Experiments on Light,' *Philos. Mag.*, 1834, Ser. 3, *5*, pp. 3- 334.

Talbot phrases this law as follows (pp. 328–329): "Since then these two thing- the intensity of light and the time of the body's remaining in any given part of e circle—are each inversely proportional to the circumference of the circle it descri, it follows that they must be directly proportional to each other; that is to say, irregular intermittent luminary whose observations are too frequent and too transit for the eye to perceive, loses so much of its apparent brightness from this cause a indicated by the proportion between the whole time of observation and the ti during which it disappears." "The rapidity of the rotation does not affect the ar- ment." To verify this reasoning, Talbot conducted experiments with reflected li using pigment surfaces and mirrors to send the light to the eye; and with transmit light using sectored discs to cut down the time of exposure of the eye to various lumin sources.

In 1835 Plateau repeats and verifies Talbot's experiments. ('Betrachtun über ein von Hrn. Talbot vergeschlagenes photometrisches Princip,' *Poggen. Ann.*, 1835, *35*, pp. 457–468). He concludes from his experiments as follows (pp. 462–4) "Nun muss zufolge des am Anfange dieses Aufsatzes dargelegten Princips die sche- bare Helligkeit der Scheibe sich zu der des Papiers verhalten wie die Vorübergangsda r eines weissen und eines schwarzen Sectors; odor was dasselbe ist, wie die Winkelbrei n eines weissen Sectors zur Summe der Winkelbreiten eines weissen und schwar n Sectors, oder endlich, was auch noch dasselbe ist, wie die Breite sämmtlicher wei r Sectoren zum ganzen Kreisumfang."

Swan, apparently working in ignorance of the writings of Talbot and Plate, in substance formulates the law anew in 1849 (see W. Swan, 'On the Gradual Prod- tion of Luminous Impressions on the Eye and Other Phenomena of Vision,' *Tra. Roy. Soc. Edinb.*, 1849, *16*, pp. 581–603. See also F. Boas, 'Ein Beweis des Talb- schen Satzes und Bemerkungen zu einigen aus demselben gezegonen Folgerung,' *Wiedem. Ann.*, 1882, *16*, 359–362; A. M. Bloch, 'Expériences sur la vision,' *Cont. Rend. de la Soc. de Biol.*, 1885, *2*, p. 495; A. Charpentier, 'Loi de Bloch relative x lumières de courte durée,' *ibid.*, 1887 *4*, p. 5; etc.

For a more modern statement of this law and one also more consistent with e relation of changes in light energy to changes in sensation, see Helmholtz, 'Handb h der physiol. Optik,' zw. Aufl., 1896, p. 483, "Wenn eine Stelle der Netzhaut n periodisch veränderlichem und regelmässig in derselben Weise wiederkehrendem Lic e getroffen wird, und die Dauer der Periode hinreichend kurz ist, so entseht ein contin- licher Eindruck, der dem gleich ist, welcher entstehen würde, wenn das während ei r jeden Periode eintreffende Licht gleichmässig über die ganze Dauer der Peri e vertheilt würde"; or E. C. Sanford, 'Experimental Psychology,' 1898, p. 146, "W n once the rate of rotation is sufficient to give a uniform sensation, the color and brig- ness of any concentric ring are the same that they would be if all the light reflec d

sensation is the same as is gotten by reducing the intensity of each light by an amount proportional to the ratio of the exposure time of that light to the total time of exposure to both lights; or in case the photometer head is a sectored disc, in proportion to the value of the given sector or set of sectors to 360°. That is, with a total value of each sector or set of sectors of 180°, the effect on sensation is the same as if each light were reduced one-half in intensity; if the total value of one sector or set of sectors is 90°, the effect on sensation is the the same as if the light illuminating that sector were reduced to one-fourth of its intensity; if the total value were 45°, the same effect is produced as if the light were reduced to one-eighth of its intensity; etc. Thus, even if the rate of succession that is used in the method of flicker could be considered as the fusion rate for the brightness component of the sensation aroused, little advantage could be gained for the position in question. For the conclusion most certainly could not be avoided that the effect on sensation would be the same as if the lights were reduced in intensity, and by an amount proportional to the ratio of exposure time of each light to the total time of exposure to both lights.

The position under discussion seems also to involve to some extent a confusion of principle of the method of flicker with the method of critical frequency. For example, in the method of critical frequency, the impressions are given to the eye at the fusion rate. We need scarcely call to mind the procedure. One sector or set of sectors of the disc is illuminated by one of the lights to be compared and the other is black or of a very low luminosity. The disc is rotated at a rate which completely fuses the sectors in sensation. This light is then removed and the other light to be compared is substituted for it. The distance of this light from the disc is then adjusted until the rate of rotation required to produce fusion is the same as it was in the previous case. When this adjustment is obtained the intensity of illumination of the disc by the two lights is said to have been the same, and the

from it were evenly distributed over its surface, and no further increase in rapidity produced any effect on its appearance."

relative brightnesses of the lights themselves are calculatec by the law of inverse squares. The situation is, however quite different for the method of flicker. Both sectors o sets of sectors of the disc are illuminated by the lights to b compared, and the rate of rotation is to be made such tha if there were any brightness difference between the sectors the maximum of flicker, not fusion, would be produced. If rate were used that would produce fusion, for example, fo any given amount of brightness difference, it is obvious tha no difference in brightness equal to or less than this amoun could be detected by the method. That is, the whole poin of the method is to use a rate of speed that could not possibl be the fusion rate for any appreciable amount of brightnes difference between the impressions to be compared; and in s far as this purpose can be realized in the different cases i which the method is employed, sensitivity for the method i obtained.

What our critic really needs to establish in order to suppor his position is that summation instead of fusion takes plac That is, if the total effect of each light on sensation is to ris to a higher level than is given by each individual impressior the individual impressions must in proportion to the ris summate or add their individual intensities. To produce thi effect of summation, each individual impression would hav to last over in sensation until the next impression of its kin is received, which, since the impressions alternate, could b the next impression but one. For example, when red an green lights are being compared, if the value of the red sensa tion is to rise to a higher level than that given by a singl impression, the sensation aroused by one exposure to re would have to last over until sensation is aroused by the ne exposure to red; that is, would have to last through the inte val of exposure to green and into and wholly or partly throug the succeeding interval of exposure to red. How highl improbable it is that this could happen to any degree th would be of saving consequence to the method, is shown by t following two considerations. (*a*) The wavering character the sensation which we call flicker is due to the fact that

given sensation does not carry over without a great loss of intensity through the next succeeding interval, let alone through the next interval but one. And (*b*) even at the rate at which complete color and brightness fusion takes place, there is according to the Talbot-Plateau law no effect of summation great enough to cause each individual sensation to attain to a higher intensity than that fixed by the ratio of the time of exposure of its stimulus light to the total time of exposure of both lights, nor to produce a noticeable change in this intensity, however great is the speed of the succession. That is, we have a reduction of the intensity of the sensation aroused by each light which is the same as would be gotten were the intensity of each light to be reduced by an amount proportional to the ratio of the time of exposure of that light to the total time of exposure of both lights, and no further increase in the rapidity of the succession produces any change in this effect.[1]

With regard to the method of flicker, then, the case apparently stands as follows. The individual impressions are so short that the eye is very much underexposed to its stimulus, and the rate of succession is so slow that there is

[1] If one were permitted to interpret the Talbot-Plateau law with regard to what takes place when a rate of succession is employed greater than the fusion rate for both the colored and brightness components of sensation, two possibilities would be opened for explaining why no change in sensation is produced as the rate of succession is increased, and the length of each individual exposure is correspondingly decreased. (1) Either the increase in the reduction of the exposure-time causes no further reduction in the sensation aroused by the individual exposures; or (2) there is, owing to the increased rate of succession, a summation effect which just compensates for the reduction of the individual impressions. Now even if we were to accept as true the one of these alternatives which is the more favorable for the case of flicker, namely, that a compensating summation action takes place, and assume that this compensating summation obtains clear down to the rate of succession that is used in the method of flicker, we would have to expect as much reduction in the sensation aroused by each of the lights as is expressed by the Talbot-Plateau law. That is, the reduction for each would be the same as would be gotten were the intensity of each light to be reduced in proportion to the exposure-time of each to the exposure-time of both. As we have already pointed out, however, it is extremely improbable that there could be a compensating summation action at the flicker rate great enough to be of any considerable consequence to the method, because the wavering character of the sensation which we call flicker is due to the fact that a given sensation does not carry over without great loss until the next one develops, let alone until the next but one develops, which it would have to do to produce any summation effect.

not enough carrying-over from impression to impression to produce fusion, let alone the summation effect which is needed to cause the intensity of the sensation to rise to its full value or perhaps even to a higher level than would be given by a single exposure. Moreover, according to the Talbot-Plateau law a summation effect great enough to cause the sensation to rise to its full value is never produced, however fast is the rate of succession; for once the fusion rate is obtained, there is a reduction of the intensity of the sensation aroused by each light which is the same as would be gotten were the intensity of each light to be reduced in proportion to the time of exposure of that light to the total time of exposure to both lights, and there is no change in this effect however much the rate of succession is increased.

[1] Since the above discussion was presented to the Illuminating Engineering Society, Ives in collaboration with Kingsbury, has published a sixth article on the method of flicker (*Philos. Mag.*, Nov., 1914, *28* (167), pp. 708–728) in which a theory of flicker photometry is developed based on an analogy drawn between the response of the eye under successive stimulation to the action of incandescent lamp filaments under a fluctuating current. The gist of the article is that if the eye behaves under the conditions obtaining in flicker photometry as do lamp filaments (subject to certain modifications which are not in accordance with what is known of the functioning of the eye) under a fluctuating current, the method of flicker should give with high intensities of light at the photometer screen the same results on the average as the equality of brightness method. It is our purpose here merely to note the article not to give a detailed discussion. The theory will be discussed in a later paper in connection with further experimental data. It may not be out of place to state at this time, however, that the analogy of the eye and the incandescent lamp filament is not based on experimental examination of the eye's manner of response, but is assumed. Moreover, considerable evidence is offered in the present paper, we think that the eye does not react to its stimulus given to it in succession at the flicker rate according to the laws which govern the temperature response of lamp filaments, more especially when the impressions differ widely as to wave-length. It has not been claimed, for example, that the flicker method does not give the same results as the equality of brightness method when the lights compared do not differ as to wave-length.

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THE EFFICIENCY OF THE EYE UNDER DIFFERENT CONDITIONS OF LIGHTING: THE EFFECT OF VARYING THE DISTRIBUTION FACTORS AND INTENSITY.*

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Synopsis: In a previous paper** a plan of work was outlined by one of the writers for the study of the effect of different kinds of lighting conditions on the eye. The problem was divided into three parts: (1) the determination of the conditions that give in general the highest level or scale of visual efficiency; (2) the conditions that give the least loss of efficiency for continued work; and (3) the determination of the conditions that cause the least discomfort. Tests were described especially designed to meet the requirements of each of these divisions of the work and results were given to show in a general way the sensitivity of the tests employed. The work of the present paper is confined to the second division of the problem and should be considered as an explorative investigation for the determination of factors. Six aspects of lighting are considered provisionally as sustaining an important relation to the eye: the evenness of the illumination, the diffuseness of light, the angle at which the light falls on the object viewed, the evenness of surface brightness, intensity and quality. Only the first five of these are dealt with in this paper. The first four are called, for convenience of reference, distribution factors. In order to produce the variation in the distribution factors needed for the purposes of the test, three types of reflectors in common use were employed—a direct, a semi-indirect, and an indirect. These reflectors were selected with reference to the object of the investigation rather than as representative in every case of any particular principle of lighting. The illumination effects produced in each case were specified in the following ways: (1) A determination was made of the average illumination of the room under each of the three installations. (2) The brightness of prominent objects in the room, such as the test card, the reflectors for the semi-indirect installation, the reading page, specular reflection from surfaces, etc., was given. (3) Photographs were made of the room from three positions under each kind of installation. These effects were then correlated with the results obtained with the eye test.

In order to determine the effect of varying intensity with a certain grouping of distribution factors, lamps of different wattage were used with each type of reflector employed in the distribution series. The

*A brief report of the work described in this paper was read by one of the writers (Ferree) at the seventh annual convention of the Illuminating Engineering Society held at Pittsburgh, September 22-25, 1913.

** Trans. I. E. S., p. 40, vol. VIII (1913).

illumination effects produced were specified by illumination and brightne measurements in the way described above, and the effects were aga correlated with the results of the eye tests conducted at each intensity illumination.

I. INTRODUCTION.

In a paper[1] presented to the annual convention of this socie last year, a plan of work was outlined by one of the writers f the study of the effect of different kinds of lighting conditio on the eye. The problem was divided into three parts: (1) t determination of the conditions that give in general the highe level or scale of visual efficiency, (2) the determination of t conditions that give the least loss of efficiency for continu work, and (3) the determination of the conditions that cause t least discomfort. Tests were described which seemed to t writer after six months of trial to be adequate for the requir ments of each of these three divisions of work, and results we given to show in a general way the sensitivity of the tests er ployed. With the beginning of the present year work on t problem proper was begun. This work has been confined to t second division of the problem, namely, the determination the conditions that give the least loss of efficiency as the resu of a period of work. It has been thought best to conduct th investigation at first along broad lines in order to determine in general way the conditions that affect the eye's ability to mainta its efficiency for continuous work. Later a more detailed e amination will be made of the ways in which these conditio have been worked out in the various types of lighting systems existence at this time.

The following aspects of lighting sustain an important relati to the eye: the evenness of the illumination, the diffuseness light, the angle at which the light falls on the object viewed, t evenness of surface brightness, intensity, and quality. The fi four of these aspects are very closely interrelated, and are a to vary together in a concrete lighting situation, although not a 1 : 1 ratio. For the purposes of this paper, therefore, whi is the report of an investigation primarily explorative, it will convenient to group these aspects together and refer to them

[1] Ferree, C. E., Tests for the Efficiency of the Eye under Different Systems Illumination and a Preliminary Study of the Causes of Discomfort; TRANS. I. E. 1913, Vol. VIII, pp. 40-61.

he distribution of light and surface brightness in the field of ision, or still more generally as distribution. In later work an ttempt will be made to study the effect of varying each in separtion, but in the work here reported upon, no especial attempt has een made to do this. The ideal condition with regard to disribution is to have the field of vision uniformly illuminated with ght well diffused and no extremes of surface brightness. When is condition is attained the illumination of the retina will shade ff more or less gradually from center to periphery, which gradtion is necessary for accurate and comfortable fixation and acommodation. Up to the present time, we have been able to finish as complete a way as we wish for the installations used the ork on distribution and part of the work on intensity. The mainder of the work will be completed early in the course of e present year.

The factors we have grouped under the heading distribution n most conveniently be discussed with reference to four types lighting in common use to-day: illumination by daylight, umination by direct lighting systems, by indirect lighting sysms, and by semi-indirect systems. In the proper illumination a room by daylight we have been able thus far to get the best nditions of distribution. Before it reaches our windows or ylights, daylight has been rendered widely diffuse by innumerle reflections, and the windows and skylights themselves acting sources have a broad area and a low intrinsic brilliancy, all of ich features contribute towards giving the ideal condition of tribution stated above, namely, that the field of vision shall uniformly illuminated with light well diffused and that there ll be no extremes of surface brightness. Of the systems of ificial lighting, the best distribution effects from the standpoint the comfort and efficiency of the eye are, speaking in general ms, given perhaps by the indirect systems. In this type of tem the source is concealed from the eye and the light is thrown inst the ceiling or some other diffusely reflecting surface in h a way that it suffers one or more reflections before it reaches eye. The direct lighting systems are designed to send the it directly to the plane of work. There is in the use of these tems a tendency to concentrate the light on the plane of work object viewed rather than to diffuse it, and, therefore, a ten-

dency to emphasize brightness extremes in the field of visio rather than to level them down. Too often, too, the eye is n properly shielded from the primary source of light, and fr quently no attempt at all is made to do this. The semi-indire systems are intended to represent a compromise between t direct and the indirect systems. A part of the light is transmitt directly to the plane of work through the translucent reflecto placed beneath, and a part is reflected to the ceiling. Thus, d pending upon the density of the reflector, this type of system m vary between the totally direct and totally indirect as extremes a share in the relative merits and demerits of each in proportion its place in the scale. It is not our purpose, however, at this ti to attempt a final rating of the comparative merits of types lighting systems. For that our work is still too young. Mor over, there are relatively good and bad fixtures of each type, a good and bad installations may be made of any system. Wh we hope to do is by the appropriate selection and variation conditions to find out what the factors are that are of importan to the eye in lighting, and from this knowledge as a starting po to work towards reconstruction.

It was stated also in our former paper that the problem deali with loss of efficiency presents two phases. We may investig (*a*) whether the eye shows a loss of efficiency after three or fo hours of work under a given lighting system, and (*b*) wheth there is progressive loss of efficiency in working several mont or years under a given system. We have confined and purpose confine our work for the present to the former aspect of t problem, because it alone falls within the scope of laborato studies and because we believe that the problem should be work out first in miniature with all the conveniences of manipulati and possibilities of precision obtaining under laboratory co ditions.

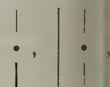
II. THE EFFECT OF VARIATION IN THE DISTRIBUTION LIGHT AND SURFACE BRIGHTNESS ON THE EF CIENCY OF THE EYE FOR A PERIOD OF WORK.

In order better to understand the data given in the tables f results, the nature of the tests used in this part of the work w again be briefly called to mind. It will be remembered that e conventional tests for the eye's responsiveness to its stimul

namely, tests for brightness sensitivity, color sensitivity, and visual acuity, were found to be practically useless for this work. Modified and rendered sensitive in the ways described in the previous paper, they were found to serve as a measure of the general level of efficiency of the unfatigued eye under different conditions of lighting; but they failed to show loss of efficiency as the result of a period of work. This is due to the following reasons. (a) There is doubtless very little, if any, loss of sensitivity to brightness and color during this length of time.[2] It is commonly believed, in fact, that the brightness and color processes are compensating in nature. And (*b*) the visual acuity test, in spite of the fact that its results may be ascribed practically entirely to changes in the muscular control of the eye, is not adapted to show loss in muscular efficiency, because the muscles of the eye, while they may have fallen off enormously in efficiency, can under the spur of the will be whipped up to their normal power long enough to make the judgment required by the test. But they can not long sustain this extra effort. This consideration, it will be remembered, led us to continue the test through an interval of time. After considerable experimentation an interval of three minutes was chosen as best suited for our purpose. When the observer is required to look at the test card for three minutes, the test objects, even when the eyes are fresh, are not seen clearly for the whole time. They are seen alternately as clear and blurred. The time they are seen clear and blurred is recorded on a rotating drum upon which a line registering seconds is also run. From this record the ratio of time seen clear to time seen blurred is determined. This ratio may be fairly taken as a measure of the efficiency of the eye for three minutes of clear seeing at the time the test is taken. In applying the test to our problem, a record is taken at the beginning and at the close of work, and the ratios of the time clear and the time

[2] That there is practically no loss of sensitivity to brightness and color for this period of time was shown in our former paper by the results of our tests for brightness and color sensitivity with and without the time element as an aid to the test. (See also in connection with tests for brightness and color sensitivity, Ferree and Rand: A Note on the Determination of the Retina's Sensitivity to Colored Light in Terms of Radiometric Units, *Amer. Jour. of Psychol.*, 1912, Vol. XXIII, pp. 328-332; An Optics-Room and a Method of Standardizing its Illumination, *Psychol. Rev.*, 1912, Vol. XIX, pp. 364-373; Colored After-Image and Contrast Sensations from Stimuli in which no Color is Sensed, *ibid*, pp. 195-239; Rand: The Factors that Influence the Sensitivity of the Retina to Color: A Quantitative Study and Methods of Standardizing, *Psychol. Rev. Monog.*, 1913, 166 pp.; The Effect of Changes in the General Illumination of the Retina upon its Sensitivity to Color, *Psychol. Rev.*, 1912, Vol. XIX, pp. 463-490.

blurred are compared for the two cases to determine how mu the eye has lost in efficiency as the result of work. Two valu were used for the distance at which the test card was plac from the eye: (*a*) the maximal distance at which the test obje could be seen clearly in the momentary judgment, and (*b*) distance less than this. The latter distance was finally chosen b- cause for the maximal distance, towards the close of the test eve when the eyes were fresh, the value of the time blurred beca too high, it was found, to make the most effective comparis of the ratios obtaining at the beginning and at the close of wo.

In order to eliminate the memory and fatigue factors whi make it impossible to reproduce results in a series of tests wi the same observer when the conventional Snellen test of visu acuity is employed, it will be remembered that the test card wa made to consist of one or more simple objects, and the type judgment was changed so that results were rendered in ter of clearness of vision instead of in terms of the ability to reco- nize a series of letters or characters.[3] That is, in this type test the observer knows what the objects are, and he records t time during which he sees them clear and the time he sees the blurred. A number of test objects were used in the work of la year: two vertical parallel lines stamped 1 mm. apart on a wh card ; the letters li printed in small type, the figures 

, etc. To these was added this year the figure 

This form of test object was suggested by the one used in D. Ives' visual acuity apparatus.[4] While apparently it gives e-

[3] For a further explanation of this point see Tests for the Efficiency of Eye under Different Systems of Lighting and a Preliminary Study of the Caus of Discomfort, TRANS. I. E. S., Vol. VIII, 1913, pp. 43-45.

[4] The writers wish to state that the test object used by them was similar that employed by Dr. Ives only with regard to form. One of the prominent featu of the apparatus used by Dr. Ives, for example, is a device for the control of width of the parallel lines and the interspaces, while the figure used by us printed on a white card with a fixed width of line and interspace. All that writers wish to point out here is that a figure made up of parallel lines and int- spaces is not, they believe, the most suitable for work of the kind we are do because of the comparatively large mean variation it gives in the ratio, time cl to time blurred.

The figure was at first made 7 mm. in diameter; but this figure was found be too large. It would blur irregularly over its surface, *i. e.*, the edges wo become indistinct when the center was clear and *vice versa*. The figure fina adopted was 3.5 mm. in diameter. This size was found to be more satisfactory our work.

cellent results for the purpose for which it was adopted by Dr. Ives, it gives too large a mean variation of ratio, time clear to time blurred, when the element of time is introduced into the visual acuity test to be of maximal service in our work. This is probably because a figure of this form is more influenced by adaptation, the streaming phenomenon,[5] and other variable physiological conditions of the retina than are, for example, the letters li. This latter object was found to be far the most satisfactory for our purpose. When used as test object the mean variation of the ratio, time clear to time blurred, for the same observer working under conditions as nearly constant as possible, is very small indeed.[6] Results will be given, therefore, in this report only for the work in which the letters li were used as test object.

In our work on distribution the tests were made in a room 30.5 ft. (9.29 m.) long, 22.3 ft. (6.797 m.) wide, and 9.5 ft. (2.895 m.) high. The artificial lighting was accomplished by means of two rows of fixtures of four fixtures each. Each row was 6 ft. (1.828 m.) from the side wall, and the fixtures were ft. apart. The reflectors were 29 in. from the ceiling for the direct system, and 16 in. for the indirect and semi-indirect. Clear tungsten lamps were used as source. The voltage was kept constant by means of a voltmeter and a finely graduated wall rheostat placed in series with the lighting circuit.

In order to get the desired variation in the distribution of light and surface brightness in the field of vision required for the purposes of the test, four types of lighting were selected. One may be called a direct system; one an indirect system; one a semi-indirect system; and one was the illumination of a room by daylight. In case of the direct system, two bulbs making an angle of 180 deg. were used for each fixture. Directly above the

[5] Ferree, C. E., The Streaming Phenomenon, *Amer. Jour. of Psychol.*, 1908, pp. 484-503; also The Intermittence of Minimal Visual Sensation, *Amer. Jour. of Psychol.*, 1908, Vol. XIX, pp. 112-130.

[6] The order of magnitude of the mean variation of the test for the fresh eye was obtained as follows. Beginning at 9 A. M., five three-minute records were run with a rest period of 20 minutes between each test. This was done with all observers on several days under each system of lighting employed. The rest period was taken in each case in a room lighted by daylight facing a wall with an evenly lighted mat surface. For a single series of five tests, the variations of the time seen clear in the three-minute period have always fallen within 1 per cent. for all the observers we have used and all systems of lighting.

lights was fastened a slightly concaved porcelain reflector 16 in in diameter. This type of fixture was not chosen with an especia reference to its representative character in any system of com mercial classification. It was chosen rather with reference t the purpose of the test. It may be said, however, that it was th one in use throughout the building in which the tests were mad and gives effects very similar to much of the lighting in actua use at the present time. In case of the indirect system, corrugate mirror reflectors were used enclosed in a brass bowl. For th semi-indirect system inverted alba reflectors 11 in. in diamete were employed. The daylight illumination came from three win dows all on one side of the room. These windows were so shel tered that it was never possible for them to receive light directl from the sun or from a brilliantly illuminated sky. Moreover the light from one of them, the one nearest the observer, wa further diffused by passing through a diffusion sash made o double thick glass ground on one side.

In order to get the effect of the distribution factors on the eye' loss of efficiency as the result of a period of work, the tests shoul be conducted with the quality and intensity of light made as nearl equal as possible. The quality of light was made approximatel the same for the three installations of artificial light by usin clear tungsten lamps in each case. It was decided to make th intensity of light as nearly equal as possible at the point of te and to give a supplementary specification of the lighting effect in the remainder of the room for the three installations of arti ficial light.[7] At the point of test the light was photometered i several directions. It was made approximately equal in the plan of the test card and as nearly as possible equal in the other direc tions.

The specification of the lighting effects in the remainder of th room has been accomplished as follows. (1) A determinatio

[7] We have not as yet made the fuller photometric specification of the roo lighted by daylight with our present arrangement of windows, curtains, etc. We ho to make the effect of varying the distribution factors in daylight illuminatio (employing windows, skylights, etc.) the study of a future study. In this study photometric analysis of the illumination effects produced will be made an especi feature.

has been made of the average illumination of the room under each of the three installations. The room was laid out in 3-ft. squares, and illumination measurements were made at 66 of the intersections of the sides of these squares. Readings were made in a plane 122 cm. above the floor with the receiving test-plate of the illuminometer in the horizontal, 45 deg. and 90 deg. positions, measuring respectively the vertical, 45 deg., and horizontal components. The 122 cm. plane was chosen because that was the height of the test object. (2) A determination was made of the brightness of prominent objects in the room, such as the test card, the reflectors for the semi-indirect installation, book of the observer, specular reflection from surfaces, etc. The brightness measurements were made by means of a Sharp-Millar illuminometer with the receiving test plate removed. The instrument was calibrated against a magnesium oxide surface obtained by depositing the oxide from the burning metal on a white card. By this method the reflecting surfaces were used as detached test plates. The readings were converted into candlepower per sq. in. by the following formula: Brightness $=$ Foot-candles$/\pi \times 144$. (3) Photographs were made of the room from three positions under each system of illumination.

In Fig. 1 (see "Further Experiments on the Efficiency of the Eye under Different Conditions of Lighting," TRANS. of the Ill. Eng. Soc., 1915, X, p. 452a)[8] the test room is drawn to scale: Plan of room, north, south, east, and west elevations.[9] In the drawing plan of room, are shown the 66 stations at which the illumination measurements were made and the position of the outlets for the lighting fixtures A, B, C, D, E, F, G, H. In the drawing, east elevation, the position of the observer at one of the points at

[8] The present paper is the second one in a series of three on the efficiency of the eye under different conditions of lighting. Before it was printed the third paper had been read at the eighth annual convention of the Illuminating Engineering Society and printed in the papers for that convention. In this paper it had been found necessary to repeat some of the data of the second paper for reference. Since both the second and third papers are now appearing simultaneously, the data that was repeated in the third paper has been omitted from the second. Wherever this has been done a cross reference is given to the third paper.

[9] For the scale drawing of the test-room, for the measurements for the direct and semi-indirect systems given in Table II, and for the photographs of the test-room, we are indebted to Mr. C. W. Jordan of the United Gas Improvement Co.

which the tests were taken is represented.[10] The other thre positions are indicated by X.

Table I (see Table I, op. cit., p. 454) shows the number an wattage of the lamps used at outlets A, B, C, D, E, F, G, H; an Table II (see Table II, op. cit., 454-455) gives the illuminatio measurements for each of the 66 stations represented in Fig. 1 made with the receiving test plate of the photometer in the hori zontal, vertical, and 45 deg. planes.

Table III has been compiled as a supplement to Table II for th purpose of making a comparative showing of the evenness of il lumination at the 122 cm. level given by the three systems of light ing. Two cases may be made of this: (1) A comparison may b made of a given component from station to station; or (2) th difference between the components may be compared. To faci itate the comparisons, (*a*) the mean variation from the averag of each of the components has been computed; and (*b*) the dif ference in the averages of the three components has been deter mined. Results for the first of these points are shown in Divisio A of the table; for the second in Division B.[11]

[10] The track along which the test card was moved was parallel to the east and we walls of the room. During the three hours of reading which intervened betwee the two tests the observer moved just far enough back from the upright supporti the mouthboard to give room for the book to be held and to permit of a comfortab reading position. The book was elevated and held approximately at an angle of 45 de When taking the test, the observer faced the north wall of the room, in such position that with the eyes in the primary position, the lines of regard were parall with the east and west walls of the room. Care was taken to have print of unifor size and distinctness for use with the three systems, and to have a page whic gave a comparatively small amount of specular reflection. The brightness values the page in the horizontal and 45 deg. positions for the three systems, are given the legends for Figs. 8, 9, and 10.

[11] It would be interesting to make this comparison for other levels in the roo and for a greater number of components. But unfortunately we have not been ab to make the number of measurements needed for this comparison. The evenness the illumination, it will be remembered, is not only of importance to the efficien of the eye with reference to the object directly viewed, but also in its influence the distribution of surface brightness. The evenness of surface brightness depen in general upon two sets of factors: (*a*) the nature and position of the reflecti surfaces in the room; and (*b*) the type of delivery of light to these surfaces.

We realize that the evenness of the illumination on the 122 cm. plane given the indirect and semi-indirect units was somewhat interfered with by the reflect of the direct system which were beneath and a little to the right of these uni when in position for the test. Also the evenness of surface brightness on t ceiling for the direct system was interfered with by the indirect and semi-indir reflectors, which were above and a little to the side of the direct units. The i fluence of this "dead apparatus" will be eliminated in the next series of instal tions. Moreover, the installation in each case was not such as to give the b effects obtainable from the type of reflector used. For example, the indirect r flectors were too close to the ceiling to give the maximum evenness of illuminati and of surface brightness for the type of reflector used. The above analysis effects is, therefore, not made for the purpose of drawing general conclusions wi regard to the type of reflector employed. It is made solely for the sake of t comparison of the illuminating effects obtained with the corresponding results f loss of efficiency.

TABLE III.[12]—(DISTRIBUTION SERIES).

Compiled from Table II to show a comparison of the evenness of the illu-
nination at the 122 cm. level given by the direct, semi-indirect, and indirect ystems. Division A shows the mean variation from the average for each of he three components of illumination; Division B, the difference in the verage value of the three components.

Division A.

System	Mean variation of the components			Percentage of mean variation of components		
	Vertical	Horizontal	45°	Vertical	Horizontal	45°
irect	1.88	1.09	1.53	38%	47%	32%
emi-indirect ..	1.68	0.66	1.32	39%	42%	36%
ndirect	1.1	0.4	0.61	30%	37%	19%

Division B.

System	Difference between components			Percentage of difference between components		
	Vertical and Horizontal	Vertical and 45°	45° and Horizontal	Vertical and Horizontal	Vertical and 45°	45° and Horizontal
rect	2.68	0.23	2.45	54%	5%	51%
ni-indirect ..	2.68	0.64	2.04	63%	15%	56%
lirect	2.13	0.31	1.82	59%	9%	55%

[12] For Tables I and II, see Tables I and II, Further Experiments on the ciency of the Eye, etc., TRANS. I. E. S., 1915, Vol. X, pp. 454-455.

Fig. 2.—Showing the test room illuminated by the direct system. The photograph wa
taken from the south end of the room at a point 4 ft. from the west wall.

Fig. 3.—Showing the test room illuminated by the semi-indirect system. The photogr
was taken from the south end of the room at a point 4 ft. from the west wall.

Fig. 4.—Showing the test room illuminated by the indirect system. The photograph was taken from the south end of the room at a point 4 ft. from the west wall.

Fig. 5.—Showing the illumination effects for the west wall of the room, direct system.

Fig. 6.—Showing the illumination for the west wall of the room, semi-indirect system.

Fig. 7.*—Showing the illumination effects for the west wall of the room, indirect system

* For Figs. 8, 9, and 10, see Figs. 2, 3, and 4, "Further Experiments on the Efficiency of the Eye, etc." TRANS. of the I. E. S., 1915, Vol. X, pp. 452a-452b.

In Figs. 2 to 10 are given photographs showing the illumination of the room and the distribution of surface brightness for the three systems. Figs. 2, 3 and 4 are taken from the south end of the room at a point 4 ft. from the west wall. These photographs were taken so as to comprehend as much of the room as was possible in one view. They include the greater part of the ceiling, floor, and north wall; six of the fixtures; and about one-half of the east wall. The difference in surface brightness for the various points of the room (including the lighting units) is, it will be noted, greatest for the direct system, next greatest for the semi-indirect system, and least for the indirect system. The indirect and semi-indirect reflectors were attached to arms of approximately equal length which could be revolved about the fixture stem as an axis. When the tests were taken, these reflectors were turned in each case to the inside position indicated in the photograph, the object being to have the two types of reflectors as nearly as possible in the same position in the field of vision for the comparative tests. The direct fixtures, it will be noted, were below and slightly outside this position. In our next series of experiments, arrangements have been made such that the reflectors can be placed in exactly the same position for each type of installation when it suits the needs of the experiment to have it so. The slight deviation from exact coincidence found in these experiments is, however, perhaps of no great consequence for the purpose of the present work especially in the case of the indirect and semi-indirect reflectors. In Figs. 5, 6 and 7, are represented the illumination effects for the west half of the room. These photographs show the distribution of light and shade on the greater part of the west wall, and the adjacent ceiling, and include two of the fixtures. In Figs. 8, 9 and 10 (see Figs. 2-4, op. cit., pp. 452a-452b) are shown the brightness measurements of all surfaces having very high or very low brilliancy. The spot measured is indicated by a cross, and the numerical value of the brightness measurement in candlepower per square inch is printed nearby. These spots are also lettered for convenience of reference in the intensity series. That is, since several installations were used in the intensity series it was found convenient to express these values in tabular form and to identify them with the surfaces measured

by means of letters. These photographs were taken from a point in the line with the four positions of the observer as near to the south wall of the room as was possible, but owing to the narrow field of the camera as compared with the binocular field, these views include, for example, only about one-half of the field of vision of the observer at the test station nearest to this end of the room. The camera's field in this position corresponds in fact very closely to the field presented to the observer seated at the center of the room. While, therefore, not all of his field of view for all the positions at which tests were made is covered by the brightness measurements shown in the photographs, still the order of magnitude of brightness differences present in the field of vision for the different systems is well represented by these measurements, as can be seen by an inspection of the preceding photographs and from the descriptions of the installations used.

In order to facilitate certain features of comparison such as, for example, of the evenness of surface brightness for each system for all of the room, for all but the sources or the sources and spots above the sources, the brightness measurements shown in Figs. 8, 9 and 10 are also given in tabular form. These measurements and the letters identifying them with the surfaces measured are given in Table IV and V. (see Table III and IV, op. cit. p. 457). In making a comparison it should be noted that the spots measured are not in all cases identical for the three systems. That is, owing to the different effects produced by the different reflectors, the same spot was not always conspicuously light or dark for the three systems. The letters E, F, G, etc. may refer, then, to entirely different spots in case of the three systems.

In Tables VI and VII (see Table V and VI, op. cit., pp. 463, 464) are shown some prominent ratios of surface brightness for the three systems.[13] In representing these ratios it has been consid-

[13] In attempting to make comparisons of the effect of the different magnitude of brightness ratios, one obviously must bear in mind that the surfaces between which the ratios are established are not in all cases in the same position in the field of vision for the three systems. For example, the brightest surfaces in case of the indirect system, namely, the spots on the ceiling directly above the reflectors are farther removed from the direct line of vision of the observer when in the working position than were the brightest surfaces in case of the direct and semi-indirect systems. The position of the surface in the field of vision would come into question, for example, in making a determination of the maximum value of brightness difference that the eye is adapted to stand. While we have done a great deal

(*Continued on next page.*)

ered important to make a comparative showing for the three systems (*a*) of the extremes of surface brightness; and (*b*) of the relation of the brilliancy of objects in the surrounding field to the surface brightness at the point of work. The extremes of surface brightness are shown by giving the ratios between surfaces of the first, second, third, etc., order of brilliancy and the surface of the lowest order of brilliancy; and the comparison of the brilliancy of objects in the surrounding field to the brightness at the point of work by giving the ratios of the surfaces of the first, second, and third order of brilliancy to the brightness of the test card and the reading page in the working position. The following points may be noted. (1) The illumination effects produced by the direct system are characterized by great extremes of surface brightness and a high ratio of brilliancy of objects in the surrounding field to the surface brightness at the point of work. These effects are much less pronounced for the semi-indirect system, and still less for the indirect. (2) A comparison of this table with the tables showing loss of efficiency as the result of work shows that while the extremes of brightness are enormously larger for the direct than for the semi-indirect system, the eye loses almost as much in efficiency for three hours of work under the semi-indirect system as under the direct. That is, the greatest ratio of brightness for the direct system is over 1,000 times as much as the greatest ratio for the semi-indirect, while the difference in loss of efficiency for the two systems is comparatively insignificant. On the other hand the greatest ratio of brightness for the semi-indirect system is only about five times as much as for the indirect and the difference in loss of efficiency for three hours of work is very large, this loss of efficiency for three hours of work for the indirect system being, it will be noted,

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of work on the effect of position of the brilliant surface in the field of vision in our investigation of the causes of discomfort, we have made no especial investigation of this point in relation to loss of efficiency. Doubtless what we shall all have to bear in mind is that even in the end we can not hope to specify narrowly what is most favorable, etc. in lighting conditions. The factors that enter into the concrete lighting situation are so complex, or rather are so variable and so rarely duplicated that we can hope to make general specifications with regard to what is most favorable, for example, only within very broad limits. If one wishes to work the conditions down to a finer point than this, the particular installation must itself be tested *in situ*. We are at present working on a shorter test which we hope will serve this purpose better than the test which has been used in the work described in this paper.

very small indeed. This seems to indicate (*a*) that for the scale of magnitudes present in this series of experiments, the gradation of surface brightness for the indirect system is very close to what the eye is prepared to stand without loss of efficiency; and (*b*) that an increase in differences in brightness above this point is followed at first by a rapid increase in loss of efficiency and later by a much slower increase. In the intensity series the following points also come out. (1) The effect of size of ratio on loss of efficiency is different for different orders of magnitude of brightness. That is, for the range of scale of magnitudes we have used, the lower is the order of magnitude, the greater is the ratio that is permissible. And (2) the size of the brilliant object as well as its brilliancy is of importance. That is, within certain limits, as yet undefined, an increase in the area of the brilliant surface causes an increase in loss of efficiency.

Supplementary to Tables IV–VII we have computed for the three systems the mean variation of the several brightness values from their average values. While important from the standpoint of showing the variation from the mean for the different systems, such a comparison is, however, probably not so important from the standpoint of the eye as are the comparisons given in Tables IV–VII. That is, from the standpoint of effect on the eye it is probably more important to give a representation of the brightness of individual surfaces, more especially of surfaces showing extremes of brightness, than it is the mean variation from the average brightness of all the surfaces. In order to make possible the comparison with and without the source and the spot above the source, the table is made to show separately the mean variation for the following measurements: (*a*) for all; (*b*) for all but the source; and (*c*) for all but the source and the spot above the source. Results are given in Table VIII.

Obviously the effect of these installations on the eye's ability to maintain its efficiency for a period of work will vary with the position of the observer in the room. The tests have been made, therefore, at four positions: one in which six fixtures were in the field of view, one in which four were in the field of view, one in which two were in the field of view, and one in which none were in the field of view. This variation of position at

which the observation was made accomplishes two purposes. (1) It gives us a more representative idea of the difference in the effect on the eye of the four types of lighting. And (2) it shows the effect of varying the number of surfaces showing brightness differences, particularly the number of primary sources in the field of view.

TABLE VIII.[14]—(DISTRIBUTION SERIES).

Compiled from Table IV to show the mean variations in surface brightness for the direct, semi-indirect, and indirect systems.[15]

Measurements considered	Mean variation for the three systems			Percentage of mean variation for the three systems		
	Direct	Semi-indirect	Indirect	Direct	Semi-indirect	Indirect
All	94.977	0.075	0.0235	189%	145%	135%
All but the source	0.0018	0.01817	0.0235	33%	120%	135%
All but the source and the spot above the source	0.0016	0.0013	0.0012	32%	30%	35%

[14] For Tables IV-VII, see Tables III-VI, Further Experiments on the Efficiency of the Eye, etc., TRANS. I. E. S., 1915, Vol. X, pp. 457, 463-464.

[15] It is scarcely necessary to point out that the above results seem to indicate that the great advantage of the indirect over the other systems of lighting we have used with regard to the factor: evenness of surface brightness, comes primarily at least from its provision for shielding the eye from the light source rather than from any conspicuously greater evenness of illumination given by it to the objects in the field of view. In fact all of the systems give a fairly even distribution of surface brightness outside of the source and the surfaces immediately surrounding it.

The need of keeping the surface brightness within certain limits and the primary importance of properly shielding the eye from the source to the accomplishment of this desideratum are both obvious Doubtless many ways will be devised in course of time for cutting down useless and harmful brightness differences in lighting effects. For example, the possibility is here suggested of producing a still smaller brightness difference than is given by the indirect reflectors of the type we have employed, by using semi-indirect reflectors of such a density as to give a surface brilliancy equal to that of the spot of light cast upon the ceiling. The value of this brilliancy, because of the larger area of luminous surface presented, could then be made smaller than that of the ceiling spot cast by the indirect reflector and still give the same amount of light to the room. A similar effect may be obtained with the indirect reflector by using lamps of lower wattage and adding the light needed to make up the deficiency by installing directly beneath the reflector lamps of low wattage in translucent enclosures of a density that will give a surface brilliancy equal to that of the ceiling spots. The effect of both of these devices would be to lower the surface brilliancy for a given light flux by increasing the area of the luminous surface. Whether either would be advisable from other standpoints we are not at present prepared to say.

Results will be given in this paper only for the position with six fixtures in the field of view. The results for the other positions will be given in a later paper. When working at the position with six fixtures in the field of view, our tests show that the eye loses practically nothing in efficiency as the result of three to four hours of work under daylight, it loses enormously for the same period of work under the direct installation, and almost as much under the semi-indirect installation. Under the indirect installation the eye loses a little more than under daylight, but not nearly so much as under the other installations.

The results of the work on distribution are given in Tables IX and X. Early in the work it was found that nearly as much difference in result was gotten for two as for three hours of work. In Table IX is shown the loss in efficiency for Observer R for three hours of work under the four systems; and in Table X, the loss in efficiency for Observer G for two hours of work. These tables are typical of the results obtained from all of our observers for these periods of work.[16] Column 1 of these tables gives the type of lighting system. Column 2 gives the total wattage of the lamps used, and Column 3 the voltage at which these lamps were operated. Columns 4, 5, and 6 give the foot-candles of illumination at the point of work measured respectively in the horizontal, vertical, and 45 deg. planes. Column 7 gives the maximal distance at which the test object could be seen clearly, and Column 8 the distance chosen at which to conduct the test for loss of efficiency. Care was taken in every case to choose this working distance of such a value that the ratio it sustained to the maximum distance was always approximately the same. Column 9 gives the total time the test object was seen clear in the three minutes of observation and Column 10 the total time it was seen blurred. Column 11 gives the ratio of the total time seen clear to the total time seen blurred, and Column 12 gives the comparative values of these ratios in terms of a common standard. These ratios were reduced to a common scale or standard in order to make the comparison of the amounts of

[16] Obviously in the consideration of the effect of a given lighting system on the ability of the eye to hold its efficiency for a period of work, the age of the observer and the condition of his eyes should be taken into account. For a full clinic report of the eyes of the observers employed, see op. cit., foot-note 14, p. 460.

change in their ratios easier. They express the comparative ability of the eye to sustain its power of clear seeing for three minutes before and after work for the four conditions of lighting used.

It will also be noted from Column 8 of the above tables that the visual acuity tests show that acuity of vision as determined by the momentary judgment is higher for the same foot-candles of illumination under daylight than under artificial light, and of the artificial lights it is very slightly highest for the indirect system, next highest for the semi-indirect system, and slightly lowest for the direct. It will thus be seen that for all the purposes of clear seeing, whether the criterion be maximal acuity or the ability of the eye to hold its efficiency for a period of work, the best results are given in order by the systems that give the best distribution. The effect of distribution, however, on the ability of the fresh eye to see clearly, is not nearly so great as it is on its power to hold its efficiency for a period of work.

In order to give a typical representation in graphic form of the effect on the efficiency of the eye of a period of work under these four conditions of lighting, the results of the above tables will also be given in the form of a chart made up of straight lines showing in each case the loss of efficiency from beginning to close of work. In constructing these charts, the length of time of work is plotted along the abscissa, and the ratio of the time the test object is seen clear to the time it is seen blurred is plotted along the ordinate. Each one of the large squares along the abscissa represents one hour of work and along the ordinate an integer of the ratio. Chart A shows the results for Table IX, and Chart B for Table X. An inspection of these charts will show how widely different in amount is the loss in efficiency under the specified conditions for the direct and semi-indirect systems as compared with the indirect system and daylight, and how close is the correspondence between the results for the direct and semi-indirect system, and between the results for the indirect system and daylight.

The loss in efficiency found in the above work seems to be predominantly, if not entirely, muscular, for the tests for the sensitivity of the retina show practically no loss in sensitivity

TABLE IX.—(DISTRIBUTION SERIES).

Observer R, showing the eye's loss in efficiency as the result of 3 hours of work under the systems of indirect, semi-indirect, and direct lighting employed as compared with daylight. 8 lamps, indirect and semi-indirect systems; 16 lamps, direct system. Intensities equalized on test card. Clear tungsten lamps.

Lighting system	Watts	Volts	Foot-candles			Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Total time clear ÷ total time blurred	Ratios reduced to common standard
			Horizontal	Vertical	45°							
Daylight	—	—	5.5	1.32	4.2	9 A.M.	90.0	74.0	137	43	3.18	3 5
						12 M.	90.0	74.0	135	45	3.0	3.3
Indirect	800	107	5.2	1.36	3.5	9 A.M.	84.5	67.5	135	45	3.0	3.5
						12 M.	84.5	67.5	132	48	2.75	3.2
Semi-indirect	760	107	5.8	1.45	4.0	9 A.M.	80.5	68.5	142	38	3.73	3.5
						12 M.	79.5	68.5	92	88	1.04	0.97
Direct	880	107	4.2	1.41	2.6	9 A.M.	81.0	68.0	139	41	3.39	3.5
						12 M.	78.0	68.0	71	109	0.65	0.67

TABLE X.—(DISTRIBUTION SERIES).

Observer G, showing the eye's loss in efficiency as the result of 2 hours of work under the systems of indirect, semi-indirect, and direct lighting employed as compared with daylight. 8 lamps, indirect, and semi-indirect systems; 16 lamps, direct system. Intensities equalized on the test card. Clear tungsten lamps.

Lighting system	Watts	Volts	Horizontal	Vertical	45°	Time	Maximal distance	Working distance	Total time clear	Total time blurred	Clear ÷ blurred	Ratios
Daylight	—	—	5.5	1.32	4.2	9 A.M.	91.0	77.0	161	19	8.45	3.50
						11 A.M.	91.0	77.0	160	20	8.00	3.31
Indirect	800	107	5.2	1.36	3.5	9 A.M.	85.0	72.0	159	21	7.57	3.50
						11 A.M.	85.0	72.0	157	23	6.83	3.15
Semi-indirect	760	107	5.8	1.45	4.0	9 A.M.	83.0	72.0	159	21	7.55	3.50
						11 A.M.	81.0	72.0	150	30	5.00	2.30
Direct	880	107	4.2	1.41	2.6	9 A.M.	81.0	69.5	145	35	4.14	3.50
						11 A.M.	78.0	69.5	131	49	2.67	2.20

Chart A (Observer R).—Showing the eye's loss in efficiency as the result of three hours of work under the systems of indirect, semi-indirect and direct lighting employed as compared with daylight.

Lighting system	Watts	Volts	Foot-candles Horizontal	Vertical	45°
A—Daylight	—	—	5.5	1.32	4.2
B—Indirect	800	107	5.2	1.36	3.5
C—Semi-indirect ...	760	107	5.8	1.45	4.0
D—Direct	880	107	4.2	1.41	2.6

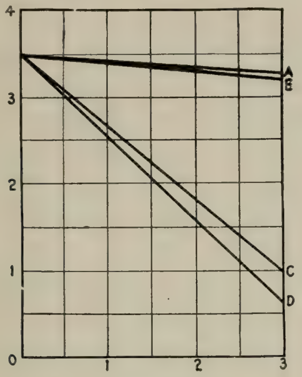

Chart A.

Chart B (Observer G).—Shows the eye's loss in efficiency as the result of two hours of work under the systems of indirect, semi-indirect and direct lighting employed as compared with daylight.

Lighting system	Watts	Volts	Foot-candles Horizontal	Vertical	45°
A—Daylight........	—	—	5.5	1.32	4.2
B—Indirect	800	107	5.2	1.36	3.5
C—Semi-indirect ...	760	107	5.8	1.45	4.0
D—Direct	880	107	4.2	1.41	2.6

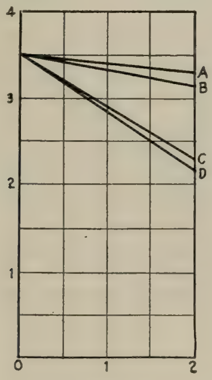

Chart B.

as the result of work under any of the installations employed.[17] The following reasons are suggested why the muscles of the eye giving both fixation and accommodation should be subjected to a greater strain by the direct and semi-indirect installations than by the indirect installation or daylight. (1) The bright images of the sources falling on the peripheral retina, which is in a perpetual state of darkness-adaptation as compared with the central retina, and is, therefore, extremely sensitive in its reaction to such intensive stimuli, set up a reflex tendency for the eye to fixate them instead of, for example, the letters which the observer is required to read. (2) Likewise a strong reflex tendency to accommodate for these brilliant sources of light, all at different distances from each other and the lettered page, is set up. (3) These brilliant images, falling on a part of the retina that is not adapted to them, causing as they do acute discomfort in a very short period of time, doubtless induce spasmodic contractions of the muscles which both disturb the clearness of vision and greatly accentuate the fatiguing of the muscles. The net result of all these causes is excessive strain which shows itself in a loss of power to do work. In the illumination of a room by daylight, however, with a proper distribution of windows, the situation is quite different. The field of vision contains no bright sources of light to disturb fixation and accommodation and to cause spasmodic muscular disturbances due to the action of the intensive light sources on the dark-adapted and sensitive peripheral retina. As we have already pointed out, the light waves have suffered innumerable reflections and the light has become diffuse. The field of vision is, comparatively speaking, uniformly illuminated, and there are no extremes of surface brightness. The illumination of the retina, therefore, falls off more or less gradually from center to periphery, as it should to permit of fixation and accommodation for a given object with a minimum amount of strain.

[17] In the next paper of the series it is shown (see op. cit. pp. 484-490) that the loss in muscular efficiency is confined largely to the accommodation muscles. The fixation muscles apparently suffer little loss for the period of work we have used.

III. THE EFFECT OF VARIATION IN THE INTENSITY OF LIGHT ON THE EFFICIENCY OF THE EYE FOR A PERIOD OF WORK.

It is not our purpose, however, to contend that distribution of light and surface brightness in the field of vision is the only factor of importance in the illumination of a room. The intensity and quality of light must also be taken into account. For example, one of the most persistent questions asked by the illuminating engineer is: "How much light should be used with a given lighting installation to give the best results for seeing?"

We have undertaken, therefore, to determine the most favorable range of intensity for the four types of lighting we have used. Our work shows in general the following results. A very wide range of intensity is permissible for daylight, and a comparatively wide range for the indirect installation. For the semi-indirect installation the eye fell off heavily in efficiency for all intensities with exception of a narrow range on either side of 2.2 foot-candles measured at the level of the eye at the point of work with the receiving surface of the photometer in the horizontal plane. For the direct installation no intensity could be found for which the eye did not lose a very great deal in efficiency as the result of work. Thus it seems that the factors we have grouped under the heading distribution are fundamental. That is, if the light is well distributed and diffuse, as it was in case of the daylight and indirect installations we used, and there are no extremes of surface brightness, the ability of the eye to hold its efficiency is, within limits, independent of intensity. In short, the retina is itself highly accommodative or adaptive to intensity, and if there is the proper distribution and diffuseness of light and the proper gradation of surface brightness in the field of vision, the conditions are not present which cause strain and consequent loss in efficiency in the adjustment of the eye. The results of this series of tests, then, accomplish two purposes. (1) They show that when the distribution and diffuseness of light and the distribution of surface brightness in the field of view are properly taken care of, the eye, so far as the problem of lighting is concerned, is practically independent of intensity. And (2) they show the effect on the efficiency of the eye of the variations in surface brightness pro-

duced by varying intensity in case of the direct and semi-indirect installations we have used.

The tests were made in the same room, with the same fixtures, and in general with the same conditions of installation and methods of working as were described in the work on distribution. To secure the various degrees of intensity needed, lamps of different wattage were used. These were selected from a series of tungsten lamps ranging from 15–100 watts. In order to keep the distribution factor as nearly constant as possible for a given type of system, the lamps used in making the test for that type of system were all of one wattage, *i. e.*, all 15's, 25's, 40's, 60's, or 100's.

For the semi-indirect system the total range of intensity of illumination employed is shown by the following figures. The series was begun with 25-watt lamps[18] and consisted of 25, 40, 60, and 100-watt lamps.[19] For the 25-watt lamps the photometer reading at the point of work with the receiving test plate of the photometer in the horizontal plane, showed 1.6 foot-candles; with the test plate in the vertical position 0.45 foot-candle; in the 45 deg. position 1.15 foot-candles. For the 100-watt lamps, 6.8 foot-candles were obtained with the test plate horizontal; 1.82 foot-candles with the test plate vertical; and 4.5 foot-candles with it in the 45 deg. position. The tests for loss in efficiency[20] showed that the intensity most favorable to the eye was secured

[18] Since the most favorable intensity was given by the 40-watt lamps and since the 15-watt lamps gave so little light as to be extremely trying to the eyes, it was thought best to begin the series with the 25-watt lamps instead of the 15 as was done in case of the direct system.

[19] Owing to their smaller size, socket extenders had to be used for the 25 and 40-watt lamps. That is, without the extenders these lamps came so low in the reflector as to change the distribution effects given by the reflector.

[20] In conducting these tests it was found necessary to allow a period of adaptation without work to the illumination of the room before the first test was taken. If this were not done, especially in case of the lower intensities of light used, the changing sensitivity of the eye to the intensity of light employed produced a noticeable change in the visual acuity between the times the tests before and after work were taken. Since the distance of the test card was kept the same for the two tests, this change in the visual acuity tended to influence the ratio: time clear to time blurred. To determine the length of time needed with a given intensity of light to insure a constant acuity so far as adaptation is concerned, preliminary tests were made as follows. The acuity of the observer was taken every three minutes until no noticeable change was found. This length of time was then always allowed for that observer as an adaptation period prior to the loss of efficiency test conducted for the intensity of illumination.

when the photometric reading with the test plate in the horizontal plane showed 2.2 foot-candles; in the vertical plane, 0.58 foot-candle; and in the 45 deg. plane, 1.52 foot-candles. The total wattage in this case was only 320. At this intensity of illumination the semi-indirect installation, so far as its effect on the eye is concerned, compares very favorably with the indirect installation at such ranges of intensity as we have employed. At intensities appreciable higher than this most favorable value, however, or appreciably lower, the loss in efficiency is very great. At the intensity commonly recommended in lighting practise, this semi-indirect installation is almost, if not quite as damaging as the direct installation. The intensity recommended by the Illuminating Engineering Society, for example, in its primer issued in 1912, ranges from 2-3 to 7-10 foot-candles, depending upon the kind of work; 5 foot-candles is taken as a medium value. This medium value is more than double the amount we have found to give the least loss in efficiency for the type and installation of semi-indirect lighting we have used. The intensity we have found to give the least loss in efficiency for this type of lighting does not, however, give maximal acuity of vision as determined by the momentary judgment. At an intensity that does give maximal acuity of vision as determined by the momentary judgment, the eye runs down rapidly in efficiency. That is, in this type of lighting one or the other of these features must be sacrificed. High acuity and little loss in efficiency can not both be had at the same intensity. These features can both be had only under daylight and, in case of the installations, we used, with the indirect system. However, the amount of light we find to give the least loss in efficiency seems to be sufficient for much of the work ordinarily done in the office or home. It is not enough, though, for drafting or other work requiring great clearness of detail. By giving better distribution effects this system is supposed also to be a concession to the welfare of the eye, but our tests show that this concession is not so great as it is supposed to be. In fact, installed at the intensity of illumination ordinarily used, or at an intensity great enough for all kinds of work, little advantage is gained for the eye in this type of lighting with reflectors of low or medium densities; for with these

intensities of light and densities of reflector, the brightness of the source has not been sufficiently reduced to give much relief to the suffering eye. Until this is done in home, office, and public lighting, we can not hope to get rid of eye strain with its complex train of mental and physical disturbances. If the semi-indirect principle of lighting is to be used with benefit to the eye, a density of reflector and type of installation must be employed that will give a gradation of brightness in the field of view in conformity with the limits of difference that the eye can stand without loss in efficiency or comfort.

In case of the direct system of lighting, we were able to improve the conditions so far as loss of efficiency of the eye is concerned, by reducing the intensity; but this system never proved to be so favorable in this regard as even the semi-indirect system. In the tests made under the direct system care was taken to have the fixtures as nearly as possible in the same position as they were for the semi-indirect system. Our fixtures for the direct system were so installed that either one or two lamps could be used in each fixture, totalling respectively 8 and 16. In order to get a wider range of intensity both numbers of lamps were used, *i. e.,* one series was made with 8 lamps and aonther with 16. Four intensities of light were used in each case. These intensities were secured in the 8-lamp system by using lamps totalling 120, 200, 320, and 480 watts. The foot-candles at the point of work ranged from 0.64 with the receiving test plate of the photometer in the horizontal, 0.32 in the vertical, and 0.49 in the 45 deg. position with the lamps totalling 120 watts, to 2.6 with the test plate in the horizontal, 1.02 in the vertical, and 2.0 in the 45 deg. position with the lamps totalling 480 watts. The four intensities were secured in the 16-lamp system by using lamps totalling 240, 365, 400, and 880 watts. The foot-candles at the point of work with the 16-lamp system ranged from 1.23 with the test plate in the horizontal, 0.54 in the vertical, and 0.935 in the 45 deg. positicn with the lamps totalling 240 wattts, to 4.2 with the test plate in the horizontal, 1.41 in the vertical, and 2.6 in the 45 deg. position with the lamps totalling 880 watts. The most favorable intensity was secured by an installation that gave 1.16 foot-candles with the test plate in the horizontal, 0.45 in the

vertical, and 0.85 in the 45 deg. position. This intensity was given by the 8-lamp system with a total wattage of 200. At this intensity, however, the loss in the efficiency of the eye for three hours of work was almost four and one-half times as great as for the most favorable intensity for the semi-indirect system; and more than four and one-half times as great as for a wide range of intensities for either the indirect system or daylight.

The following specification was made of the illumination effects for the intensity series. (1) Illumination measurements were made for the highest intensity employed at the 66 stations in the test room. These measurements were made in the way described in the preceding section. For the other intensities employed, measurements were made at 9 representative stations to show in a general way the order of magnitude of reduction produced by using the lamps of lower wattages. (2) Brightness measurements were made of prominent objects in the room, such as the test card, the book of the observer, and all surfaces showing very high or very low brilliancy, for all intensities for all systems.

In Table XI are given the illumination measurements for the highest wattages used made with the receiving test plate of the photometer in the horizontal, vertical, and 45 deg. planes. Tables XII, XIII and XIV show the illumination measurements for the other wattages employed in the series at nine representative stations. These measurements are intended to show the order of magnitude of reduction of the illumination of the room produced by using the lamps of lower wattage. They conform in each case pretty closely, it will be noted, to the simple ratio of the wattages employed. Tables XV, XVI and XVII give the brightness measurements for these installations for the different intensities used. The points at which the measurements were taken are indicated by the letters A, B, C, D, E, F, etc., see Figs. 8 and 9. In Tables XVIII, XIX and XX are given the prominent brightness ratios for the different intensities used. It was stated in the preceding section that the order of magnitude of the brightness scale exerts an influence on the effect of brightness ratio on the eye's loss of efficiency. This influence is readily seen on comparing the results of Table XVIII with those of

Table XXI. That is, while the various brightness ratios remain pretty much the same for the different intensities of light employed, the least loss of efficiency was given by the 40-watt lamps. This loss was, for example, very much less than was given by the 100-watt lamps, not quite so much less than was given by the 60-watt lamps, and very little less than was given by the 25 watt lamps. The loss in efficiency for the 25-watt lamps can also doubtless be attributed in part to an insufficient amount of light. At least the testimony of the various observers was that not enough light was given by these lamps for ease and comfort in reading. The results of these experiments seem to show, then, that a given order of magnitude of brightness difference in the field of view has more effect on the efficiency of the eye when the general scale of brightness values is higher than when it is low.

A comparison of Tables XIX and XX with Tables XXII and XXIII shows the influence of the area of the bright surface on the ability of the eye to hold its efficiency for a period of work. For example, although it is shown in Table XIX that the ratios: lightest surface to darkest surface, and lightest surface to test card and reading page, are greater in the 16-lamp system for the 15 than for the 25-watt lamps, Table XXII shows that greater loss of efficiency is caused by the 25-watt lamps. Similarly, Table XX shows that in the 8-lamp system these ratios are greater for the 25 and 40 than for the 60-watt lamps, while Table XXIII shows that the 60-watt lamps cause the greater loss in efficiency. This may be explained as follows. The brightest surfaces in the field of vision for the direct system are the filaments of the lamps. The brightness measurements given in the table are in terms of candlepower per square inch. The candlepower per square inch is the same, for example, for the filaments of the 15 as for those of the 25-watt lamps. But since the darkest surfaces, the test card, and the reading page, are darker for the 15-watt than for the 25-watt system, the ratios: lightest to darkest surface, lightest surface to test card, and lightest surface to reading page, are greater for the 15 than for the 25-watt system. While, however, the candlepower per square inch is the same for the 15 as for the 25-watt filaments, the actual candle-

power is less for the 15-watt filaments because of their smaller area of surface. That is, the area of the brilliant surface or in terms of luminous effects, its actual candlepower must be taken into account in estimating the effect on the eye as well as the candlepower per square inch. The effect of area on sensation is well known in physiological optics (for example, see Abney, Philos. TRANS., 1897, CXC, A, p. 169), and is expressed in the law that within limits an increase of area of the stimulus functions as an increase of intensity, although not in a simple ratio. Apparently, too, in its effect on the eye's power to maintain its efficiency for a period of work, an increase of area of the brilliant surface also functions within limits as an increase in intensity.[21] Ratios expressed in candlepower per square inch do not seem therefore, in all cases to be an adequate specification of surface brightness, so far as its effect on the efficiency of the eye is concerned, unless the areas compared be the same.

[21] The above explanation is, however, not complete. It shows only that the ratios: lightest to darkest surface, and lightest surface to test card and reading page, are greater for the 15 than for the 25-watt lamps because the candlepower per square inch not the actual candlepower was used in computing the ratios.

We are not at present able to give the ratio of actual candlepower of lightest to darkest, lightest to reading page, etc., because we did not measure the actual candlepower of the darkest surface, the reading page, etc., only the candlepower per square inch. However, since the test card and the reading page were of the same area in case of the different intensities, and the darkest surface of approximately the same area, ratios based on the total candlepower of the lightest surface (the lamp filament) and the candlepower per square inch of the darkest surface, test card, and reading page have comparative values. These ratios are very little different for the 15- and 25-watt lamps. That is, the ratio lightest to darkest for the 15-watt lamps = 28,698, for the 25-watt lamps = 28,933; lightest to test card for the 15-watt lamps = 11,828, for the 25-watt lamps = 12,616; lightest to reading page for the 15-watt lamps = 7,352; for the 25-watt lamps = 7,483.

A complete explanation of the result will doubtless involve two factors (1) the ratio of the actual candlepower of the lightest and darkest surfaces; and (2) the point brought out in connection with Tables XVIII and XXI, namely that a given order of magnitude of brightness difference in the field of view has more effect on the loss of efficiency of the eye when the general scale of brightness values is high than when it is low. From this we would expect, for example, that if the ratio lightest to darkest surface and lightest surface to test card and reading page were equal or approximately so for the 25- and 15-watt lamps, for example, the greater loss of efficiency should come with the lamps of higher wattage. Similarly for the 8-lamp system, the 60- and 40-watt lamps should cause a greater loss of efficiency than the 25-watt lamps. The 15-watt lamps with this system gave too little light to read with ease and comfort hence are ruled out of count in the comparison.

For investigating in detail the effect of area of the brilliant surface on the eye's loss of efficiency, the campimeter may prove of convenience and of service. This is one of the instances where the abstract may be used to advantage to supplement the concrete method of investigation. (See Memorandum on the Report of the Research Committee, TRANS. I. E. S., 1914, Vol. IX, No. 4, p. 358.)

The great difficulty with the abstract type of investigation, as the writers see the case at this time, is that a determination of what is permissible with regard to one factor in isolation may not be at all permissible in conjunction with other factors. A more feasible plan seems to us to be to vary the factor over a certain practical range in an actual concrete situation. By a proper selection of the concrete situations employed the ground of all that is practicable in lighting can be covered, and the results obtained can have a safe application.

TABLE XI.—(INTENSITY SERIES.)

Showing the illumination measurements in foot-candles at each of the 66 stations represented in Fig. 1 for the highest wattage used in the intensity series for the semi-indirect system, and the direct system (16 lamps and 8 lamps).

	Horizontal			Vertical			45°		
Station	Semi-indirect 800 watts	Direct (8 lamps) 480 watts	Direct (16 lamps) 400 watts	Semi-indirect 800 watts	Direct (8 lamps) 480 watts	Direct (16 lamps) 400 watts	Semi-indirect 800 watts	Direct (8 lamps) 480 watts	Direct (16 lamps) 400 watts
1	1.74	1.17	0.75	—	—	—	—	—	—
2	1.86	1.10	0.63	—	—	—	—	—	—
3	1.80	1.33	0.76	—	—	—	—	—	—
4	1.66	0.91	0.76	—	—	—	—	—	—
5	2.68	1.50	1.40	—	—	—	—	—	—
6	4.00	1.90	1.25	—	—	—	—	—	—
7	4.40	2.10	1.20	—	—	—	—	—	—
8	3.80	3.30	1.90	—	—	—	—	—	—
9	2.85	2.20	1.25	—	—	—	—	—	—
10	1.86	1.12	0.70	—	—	—	—	—	—
11	1.88	1.42	0.90	—	—	—	—	—	—
12	2.90	2.80	2.60	0.55	0.45	0.44	1.00	1.70	1.42
13	5.50	5.00	3.40	0.67	0.40	0.41	2.85	3.00	1.75
14	6.80	2.60	1.70	0.74	0.49	0.45	3.40	1.50	0.98
15	6.80	2.25	1.73	0.74	0.50	0.41	3.40	1.18	0.92
16	6.80	4.40	4.00	0.69	0.41	0.41	3.60	2.40	2.40
17	3.50	2.60	2.40	0.67	0.41	0.45	1.74	1.48	1.80
18	2.00	1.10	1.10	0.60	0.47	0.48	1.11	0.63	0.67
19	2.95	1.39	1.40	1.14	0.67	0.70	1.94	1.00	1.12
20	4.50	2.40	2.50	1.13	0.80	0.92	3.80	1.60	1.75
21	7.00	3.80	3.00	1.60	1.18	1.20	4.30	2.40	2.24
22	6.70	2.40	1.90	1.48	0.83	0.66	4.10	1.54	1.28
23	6.60	3.00	2.00	1.50	1.01	0.75	4.35	2.10	1.30
24	6.40	5.00	2.90	1.62	1.67	1.00	4.20	3.35	2.00

TABLE XI. -(INTENSITY SERIES.)—(*Continued*).

Station	Horizontal			Vertical			45°		
	Semi-indirect 800 watts	Direct (8 lamps) 480 watts	Direct (16 lamps) 400 watts	Semi-indirect 800 watts	Direct (8 lamps) 480 watts	Direct (16 lamps) 400 watts	Semi-indirect 800 watts	Direct (8 lamps) 480 watts	Direct (16 lamps) 400 watts
25	4.20	2.80	2.30	1.40	1.15	0.82	2.50	2.00	1.45
26	2.23	1.46	1.10	—	—	—	—	—	—
27	2.45	1.42	1.20	—	—	—	—	—	—
28	3.95	2.80	2.20	1.54	1.22	0.83	3.10	2.30	1.82
29	6.80	5.80	4.10	1.82	1.48	1.00	4.30	4.20	2.82
30	6.70	3.20	1.70	1.78	1.11	0.75	5.10	2.50	1.40
31	7.40	2.85	2.10	2.20	1.06	0.81	5.20	2.35	1.60
32	7.10	5.15	4.00	2.10	1.18	1.20	5.20	3.80	2.90
33	4.10	3.50	2.40	1.75	1.05	0.98	3.20	2.70	2.05
34	4.60	2.65	2.35	1.76	1.35	1.41	3.40	2 20	2.10
35	6.80	4.00	3.10	2.40	2.00	1.44	5.20	3.30	2.50
36	6.40	3.60	2.00	2.45	1.61	1.00	4.70	2.50	1.68
37	6.20	3.20	1.70	2.48	1.64	0.95	4.75	2.70	1.42
38	7.00	4.30	3.20	2.52	2.15	1.50	5.40	3.50	2.40
39	4.40	3.00	2.70	1.95	1.50	1.44	3.68	2.60	2.20
40	2.37	1.26	1.10	—	—	—	—	—	—
41	1.70	1.43	0.95	—	—	—	—	—	—
42	3.30	2.70	2.40	2.00	1.42	1.15	3.30	2.40	2.25
43	7.00	4.90	3.60	2.38	1.87	1.17	5.62	4.10	3.00
44	7.10	3.70	2.00	2.88	1.48	1.00	5.78	2.65	2.00
45	6.80	3.60	2.05	2.65	1.54	1.15	5.60	2.35	2.10
46	7.10	4.70	4.00	2.58	1.45	1.20	5.40	3.70	2.95
47	3.65	2.50	2.45	1.82	1.24	1.17	3.20	2.30	2.20
48	3.70	2.60	2.50	1.92	1.45	1.50	3.50	2.15	1.80
49	6.20	3.60	3.00	2.45	2.10	1.60	5.00	3.10	2.18
50	6.00	2.50	2.00	2.70	1.80	1.24	5.20	2.55	1.85

TABLE XI.—(INTENSITY SERIES.)—(*Continued*).

	Horizontal			Vertical			45°		
Station	Semi-indirect 800 watts	Direct (8 lamps) 480 watts	Direct (16 lamps) 400 watts	Semi-indirect 800 watts	Direct (8 lamps) 480 watts	Direct (16 lamps) 400 watts	Semi-indirect 800 watts	Direct (8 lamps) 480 watts	Direct (16 lamps) 400 watts
51	5.50	2.50	1.90	2.52	1.78	1.26	5.10	2.50	1.90
52	4.85	3.60	3.10	2.55	2.10	1.60	4.65	3.30	2.75
53	3.20	2.30	2.30	1.73	1.54	1.26	3.10	2.25	1.92
54	2.47	3.00	4.00	1.77	1.80	2.10	2.65	3.10	3.20
55	4.70	4.00	3.55	2.28	1.68	1.30	4.35	3.80	2.80
56	5.40	2.10	1.90	2.98	1.82	1.25	5.60	2.50	2.10
57	5.10	2.30	1.67	2.95	1.74	1.35	5.30	2.60	2.15
58	5.20	4.40	4.30	2.60	1.69	1.88	5.28	3.60	3.35
59	2.90	2.45	2.50	2.35	1.38	1.20	3.60	2.50	2.22
60	2.52	1.94	1.70	1.82	1.49	1.37	2.72	2.35	2.51
61	3.92	2.20	2.08	2.90	2.25	1.80	4.80	3.40	2.70
62	3.52	1.64	1.47	2.87	1.86	1.50	4.70	2.35	1.96
63	3.42	1.66	1.40	2.62	1.86	1.40	4.30	2.40	1.96
64	3.32	2.10	2.20	2.37	2.20	1.72	4.10	3.10	3.00
65	2.30	1.43	1.62	1.66	1.74	1.38	3.00	2.35	2.25
66	1.40	0.90	0.97	—	—	—	—	—	—
Average	4.44	2.72	2.14	1.93	1.48	1.12	4.03	2.55	2.06

TABLE XII.—(INTENSITY SERIES.)

Showing the illumination measurements in foot-candles at nine representative stations for the different intensities used for the semi-indirect system.

Station	Horizontal				Vertical				45°			
	800 watts	480 watts	320 watts	200 watts	800 watts	480 watts	320 watts	200 watts	800 watts	480 watts	320 watts	200 watts
Card	6.8	3.3	2.2	1.6	1.82	0.94	0.58	0.45	4.5	2.4	1.52	1.15
12	2.9	1.79	1.0	0.75	0.55	0.35	0.22	0.17	1.49	0.76	0.51	0.4
16	6.8	3.2	2.0	1.32	0.69	0.44	0.23	0.15	3.6	1.75	1.03	0.68
31	7.4	3.6	2.2	1.6	2.2	0.94	0.58	0.44	5.2	2.4	1.53	1.15
34	4.6	2.1	1.45	0.95	1.76	0.9	0.58	0.43	3.4	1.68	1.12	0.74
39	4.4	1.79	1.17	0.93	1.95	0.86	0.54	0.41	3.68	1.52	0.95	0.73
45	6.8	3.3	2.2	1.4	2.65	1.3	0.82	0.58	5.6	2.7	1.7	1.19
54	2.47	1.31	0.87	0.7	1.77	1.15	0.62	0.48	2.65	1.47	0.95	0.76
58	5.2	2.82	1.9	1.44	2.6	1.35	0.87	0.63	5.28	2.68	1.8	1.3
Average	4.44	2.66	1.78	1.11	1.93	1.16	0.77	0.48	4.03	2.42	1.61	1.01

TABLE XIII.—(INTENSITY SERIES.)

Showing the illumination measurements in foot-candles at nine representative stations for the different intensities used for the direct system (16 lamps).

Station	Horizontal			Vertical			45°		
	400 watts	365 watts	240 watts	400 watts	365 watts	240 watts	400 watts	365 watts	240 watts
Card	1.86	2.1	1.23	0.8	0.6	0.54	1.46	1.33	0.935
12	2.6	1.45	1.43	0.44	0.275	0.265	1.42	0.68	0.85
16	4.0	4.4	2.6	0.47	0.34	0.385	2.4	2.4	1.55
31	2.1	2.1	1.45	0.81	0.735	0.575	1.6	1.68	1.1
34	2.35	2.3	1.84	1.41	1.49	1.08	2.1	2.5	1.57
39	2.7	2.6	1.5	1.44	1.55	0.825	2.2	2.4	1.19
45	2.2	1.75	1.45	1.27	1.3	0.77	2.1	1.95	1.23
54	4.0	1.6	1.34	2.1	1.13	0.78	3.2	1.64	1.38
58	4.3	2.3	2.5	1.88	1.25	1.02	3.35	2.1	2.1
Average	2.14	—	1.26	1.12	—	0.67	2.06	—	1.21

TABLE XIV.—(INTENSITY SERIES.)

Showing the illumination measurements in foot-candles at nine representative stations for the different intensities used for the direct system (8 lamps).

Station	Horizontal				Vertical				45°			
	480 watts	320 watts	200 watts	120 watts	480 watts	320 watts	200 watts	120 watts	480 watts	320 watts	200 watts	120 watts
Card	2.6	1.97	16	0.64	1.02	0.65	0.45	0.32	2.0	1.39	0.85	0.45
12	2.8	1.94	.36	0.69	0.45	0.41	0.21	0.15	1.7	1.12	0.76	0.41
16	4.4	2.8	2.4	1.22	0.41	0.36	0.2	0.11	2.4	1.88	1.44	0.66
31	2.95	2.1	1.34	0.71	1.06	0.71	0.28	0.32	2.35	1.45	1.03	0.6
34	2.65	1.76	1.3	0.76	1.35	1.01	0.92	0.4	2.2	1.45	1.24	0.56
39	3.0	2.2	1.25	0.7	1.5	1.0	0.66	0.44	2.6	1.8	1.05	0.65
45	3.6	2.1	1.2	0.69	1.54	1.07	0.72	0.46	2.35	1.84	1.15	0.65
54	3.0	2.2	1.22	0.68	1.54	1.1	0.59	0.4	3.1	2.4	1.18	1.63
58	4.4	3.1	2.1	1.3	1.69	1.22	0.77	0.52	3.6	2.5	1.68	0.96
Average.	2.72	1.81	1.13	0.68	1.48	0.99	0.62	0.37	1.12	c.75	0.47	0.28

TABLE XV.—(INTENSITY SERIES.)

Showing the brightness measurements in candlepower per square inch for the different intensities used for the semi-indirect system at points indicated by the letters A, B, C, D, etc., see Fig. 3, Further Experiments on the Efficiency of the Eye, etc., TRANS. I. E. S. (1915), vol. X, p. 452b.

Position	800 watts	480 watts	320 watts	200 watts
A..................................	0.687	0.370	0.180	0.1428
B	0.0461	0.0219	0.01402	0.01008
C	0.0858	0.0504	0.0346	0.02414
D	0.0461	0.0219	0.0163	0.01008
E	0.00264	0.00177	0.0008	0.00061
F	0.0034	0.00187	0.001034	0.000792
G	0.0058	0.00242	0.00187	0.00123
H	0.00662	0.00259	0.00162	0.00144
I	0.00638	0.00237	0.00187	0.00123
J	0.00149	0.00076	0.c00484	0.000325
K	0.00462	0.00189	0.0014	0.000902
L..................................	0.00255	0.00173	0.001085	0.00063
M	0.00572	0.00224	0.001408	0.0011
N	0.00286	0.00173	0.001085	0.00063
O..................................	0.00704	0.00462	0.00264	0.00176
P	0.00616	0.003196	0.00198	0.00154
X	0.003432	0.00176	0.00105	0.000814
Reading page horizontal	0.0107	0.00462	0.0029	0.002024
Reading page 45° position	0.00654	0.00316	0.00193	0.00176

TABLE XVI.—(INTENSITY SERIES.)

Showing the brightness measurements in candlepower per square inch for the different intensities used for the direct system (16 lamps) at points indicated by the letters A, B, C, D, etc., see Fig. 2, Further Experiments on the Efficiency of the Eye, etc., TRANS. of the I. E. S., 1915, X, p. 452a.

Position	400 watts	365 watts	240 watts
A	1000.00000	1000.00000	1000.00000
B	0.1897	0.1232	0.1232
C	0.00253	0.00151	0.00151
D	0.00277	0.00145	0.00119
E	0.00097	0.00067	0.000545
F	0.00277	0.00185	0.00156
G	0.00303	0.00246	0.00172
H	0.00303	0.00229	0.00174
I	0.00316	0.00216	0.0018
J	0.00075	0.0004	0.000453
K	0.00252	0.00167	0.00176
L	0.00191	0.00149	0.00154
M	0.00273	0.00198	0.00194
N	0.00176	0.00145	0.00136
O	0.0026	0.00242	0.00143
P	0.00215	0.00167	0.00119
Q	0.00184	0.00103	0.00103
X	0.00172	0.00132	0.001
Reading page horizontal	0.00396	0.00405	0.00211
Reading page 45° position	0.0029	0.00273	0.00176

TABLE XVII.—(INTENSITY SERIES).

Showing the brightness measurements in candlepower per square inch for the different intensities used for the direct system (8 lamps) at points indicated by the letters A, B, C, D, etc., see Fig. 2, Further Tests for the Efficiency of the Eye, etc., TRANS. of the I. E. S., 1915, X, p. 452a.

Position	480 watts	320 watts	200 watts	120 watts
A	1000.00000	1000.00000	1000.00000	1000.00000
B	0.2953	0.2398	0.1657	0.08998
C	0.00317	0.00299	0.00154	0.00097
D	0.00454	0.0033	0.00185	0.000704
E	0.001848	0.00118	0.00059	0.0003
F	0.00198	0.00272	0.00145	0.00063
G	0.00347	0.00361	0.00189	0.00074
H	0.00391	0.00334	0.00122	0.0011
I	0.00405	0.0029	0.00167	0.00092
J	0.00069	0.00046	0.00037	0.00023
K	0.00308	0.00167	0.00122	0.00073
L	0.00229	0.00141	0.00103	0.00056
M	0.00387	0.00229	0.00141	0.00068
N	0.00192	0.00128	0.00096	0.00054
O	0.00246	0.00252	0.00101	0.00065
P	0.00192	0.00185	0.00083	0.00051
Q	0.00325	0.00222	0.00136	0.000704
X	0.002376	0.00141	0.000924	0.00062
Reading page horizontal	0.00528	0.00334	0.00229	0.00123
Reading page 45° position	0.003696	0.0022	0.00149	0.00077

TABLE XVIII.—(INTENSITY SERIES.)

Showing some prominent ratios of surface brightness for the different intensities used for the semi-indirect system.

Ratio	800	480	320	200
Lightest to darkest.........	0.687 /0.00149 = 455	0.37 /0.00076 = 486	0.18 /0.000484 = 372	0.1428 /0.000325 = 439
Lightest to test card........	0.687 /0.00343 = 200	0.37 /0.00176 = 210	0.18 /0.00105 = 171	0·1428 /0.000814 = 175
Lightest to reading page ...	0.687 /0.00654 = 105	0.37 /0.00316 = 113	0.18 /0.00193 = 93	0.1428 /0.00176 = 81
2nd lightest to darkest	0.0858/0.00149 = 57	0.0504/0.00076 = 66	0.0346/0.000484 = 71	0.02414/0.000325 = 74
2nd lightest to test card	0.0858/0.00343 = 25	0.0504/0.00176 = 28	0.0346/0.00105 = 32	0.02414/0.000814 = 29
2nd lightest to reading page.	0.0858/0.00654 = 13	0.0504/0.00316 = 15	0.0346/0.00193 = 17	0.02414/0.00176 = 13
3rd lightest to darkest......	0.0461/0.00149 = 31	0.0219/0.00076 = 29	0.0163/0.000484 = 34	0.01008/0.000325 = 31
3rd lightest to test card.....	0.0461/0.00343 = 13	0 0219/0.00176 = 12	0.0163/0.00105 = 15	0.01008/0.000814 = 12
3rd lightest to reading page.	0.0461/0.00654 = 7	0.0219/0.00316 = 6.9	0.0163/0.00193 = 8	0.01008/0.00176 = 6

TABLE XIX.—(INTENSITY SERIES).

Showing some prominent ratios of surface brightness for the different intensities used for the direct system (16 lamps).

Ratios	400	365	240
Lightest to darkest	1000.00000/0.00075 = 1,333,333	1000.00000/0.0004 = 2,500,000	1000.0000/0.000453 = 2,207,505
Lightest to test card.........	1000.00000/0.00172 = 581,395	1000.00000/0.00132 = 757,575	1000.0000/0.0011 = 909,090
Lightest to reading page...........	1000.00000/0.0029 = 344.828	1000.00000/0.00273 = 366,300	1000.0000/0.00176 = 568,181
2nd lightest to darkest.............	0.1897 /0.00075 = 253	0.1232 /0.0004 = 308	0.1232/0.000453 = 272
2nd lightest to test card	0.1897 /0.00172 = 110	0.1232 /0.00132 = 93	0.1232/0.0011 = 112
2nd lightest to reading page.......	0.1897 /0.0029 = 65	0.1232 /0.00273 = 46	0.1232/0.00176 = 70
3rd lightest to darkest..............	0.00316/0.00075 = 4.2	0.00246/0.0004 = 6.15	0.0018/0.000453 = 4
3rd lightest to test card	0.00316/0.00172 = 1.8	0.00246/0.00132 = 1.8	0.0018/0.0011 = 1.6
3rd lightest to reading page........	0.00316/0.0029 = 1.1	0.00246/0.00273 = 0.9	0.0018/0.00176 = 1.02

TABLE XX.—(INTENSITY SERIES.)

Showing some prominent ratios of surface brightness for the different intensities used for the direct system (8 lamps).

Ratio	480	320	200	120
Lightest to darkest	1000.00000/0.00069 = 1,449,275	1000.0000/0.00046 = 2,173,913	1000.00000/0.00037 = 2,702.702	1000.000000/0.00023 = 4,347,826
Lightest to test card	1000.00000/0.002376 = 420,168	1000.0000/0.00141 = 709,220	1000.00000/0.000924 = 1,086,960	1000.000000/0.00062 = 1,612,903
Lightest to reading page	1000.00000/0.003696 = 270,270	1000.0000/0.0022 = 454,545	1000.00000/0.00149 = 671,141	1000.000000/0.00077 = 1,298,701
2nd lightest to darkest	0.2953 /0.00069 = 428	0.2298/0.00046 = 519	0.1657 /0.00037 = 449	0.08995 /0.00023 = 390
2nd lightest to test card	0.2953 /0.002376 = 124	0.2298/0.00141 = 170	0.1657 /0.000924 = 179	0.08995 /0.00062 = 128
2nd lightest to reading page	0.2953 /0.003696 = 80	0.2298/0.0022 = 109	0.1657 /0.00149 = 111	0.08995 /0.00077 = 117
3rd lightest to darkest	0.00454/0.00069 = 6.6	0.0033/0.00046 = 7.1	0.00185/0.00037 = 5.0	0.000704/0.00023 = 3.1
3rd lightest to test card	0.00454/0.002376 = 1.9	0.0033/0.00141 = 2.3	0.00185/0.000924 = 2.0	0.000704/0.00062 = 1.1
3rd lightest to reading page	0.00454/0.003696 = 1.2	0.0033/0.0022 = 1.5	0.00185/0.00149 = 1.2	0.000704/0.00077 = 0.9

TABLE XXI.—(INTENSITY SERIES.)

Observer R, showing the effect on the efficiency of the eye of varying the intensity of light in the semi-indirect lighting system.

Watts	Volts	Foot-candles			Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Total time clear ÷ total time blurred	Ratios reduced to common standard
		Horizontal	Vertical	45°							
320	107	2.2	0.58	1.52	9 A.M.	73.5	58.5	117	63	1.86	3.5
					12 M.	71.5	58.5	112	68	1.65	3.1
320	110	2.31	0.62	1.61	9 A.M.	74.0	57.0	140	40	3.5	3.5
					12 M.	72.0	57.0	135	45	3.0	3.0
200	110	1.72	0.484	1.29	9 A.M.	72.5	57.5	138	42	3.27	3.5
					12 M.	72.5	57.5	130	50	2.6	2.78
200	107	1.6	0.45	1.15	9 A.M.	65.5	51.5	141	39	3.61	3.5
					12 M.	65.5	51.5	123	57	2.14	2.07
480	107	3.3	0.94	2.4	9 A.M.	79.0	63.5	124	56	2.21	3.5
					12 M.	76.5	63.5	96	180	1.11	1.75
800	107	6.8	1.82	4.5	9 A.M.	85.5	66.5	126	54	2.33	3.5
					12 M.	82.5	66.5	62	118	0.525	0.78
760	107	5.8	1.45	4.0	9 A.M.	80.5	68.5	142	38	3.73	3.5
					12 M.	79.5	68.5	92	88	1.04	0.97

TABLE XXII.—(INTENSITY SERIES.)

Observer R, showing the effect on the efficiency of the eye of varying the intensity of light in the direct lighting system. (16 lamps.)

Watts	Volts	Foot-candles			Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Total time clear ÷ Total time blurred	Ratios reduced to common standard
		Horizontal	Vertical	45°							
240	107	1.23	0.54	0.935	9 A.M.	74.0	62.0	132	48	2.75	3.5
					12 M.	73.0	62.0	97	83	1.17	1.49
365	107	1.6	0.6	1.33	9 A.M.	74.5	64.0	111	69	1.61	3.5
					12 M.	74.0	64.0	68	112	0.607	1.32
400	107	1.86	0.8	1.46	9 A.M.	76.0	65.0	142	38	3.68	3.5
					12 M.	75.0	65.0	102	78	1.3	1.23
880	107	4.2	1.41	2.6	9 A.M.	81.0	68.0	139	41	3.39	3.5
					12 M.	78.0	68.0	71	109	0.65	0.67

TABLE XXIII.—(INTENSITY SERIES.)

Observer R, showing the effect on the efficiency of the eye of varying the intensity of light in the direct lighting system. (8 lamps.)

200	107	1.16	0.45	0.85	9 A.M.	72.0	56.0	122	58	2.1	3.5
					12 M.	71.0	56.0	105	75	1.4	2.3
120	107	0.64	0.32	0.49	9 A.M.	70.5	56.5	141	39	2.87	3.5
					12 M.	70.0	56.5	110	70	1.57	1.91
320	107	1.97	0.65	1.39	9 A.M.	73.5	60.5	137	43	3.18	3.5
					12 M.	73.0	60.5	107	73	1.46	1.6
480	107	2.6	1.02	2.0	9 A.M.	76.0	63.5	159	21	7.57	3.5
					12 M.	73.5	63.5	128	52	2.5	1.15

Showing the effect on the efficiency of the eye of varying the intensity of light in the semi-indirect lighting system.

	Watts	Volts	Foot-candles Hori-zontal	Foot-candles Verti-cal	45°
A . .	200	107	1.6	0.45	1.15
B . .	200	110	1.72	0.484	1.29
C . .	320	107	2.2	0.58	1.52
D . .	320	110	2.31	0.62	1.61
E . .	480	107	3.3	0.94	2.4
F . .	800	107	6.8	1.82	4.5
X . .	760	107	5.8	1.45	4.0

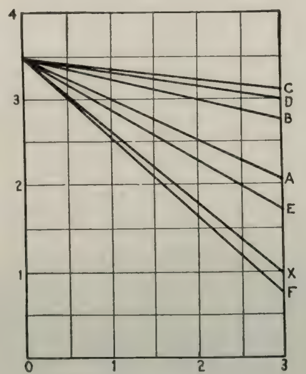

Chart C.

Showing the effect on the efficiency of the eye of varying ihe intensity of light in the direct lighting system. (16 lamps.)

	Watts	Volts	Foot-candles Hori-zontal	Foot-candles Verti-cal	45°
A . .	240	107	1.23	0.54	0.935
B . .	365	107	1.6	0.6	1.33
C . .	400	107	1.86	0.8	1.46
X . .	880	107	4.2	1.41	2.6

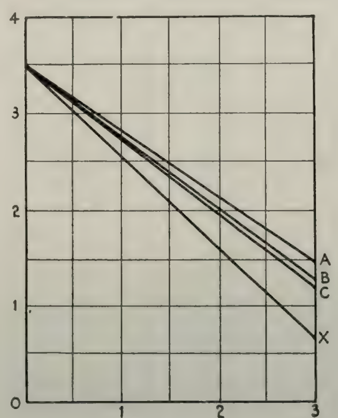

Chart D.

Showing the effect on the efficiency of the eye of varying the intensity of light in the direct lighting system. (8 lamps.)

	Watts	Volts	Foot-candles Hori-zontal	Foot-candles Verti-cal	45°
A . .	120	107	0.64	0.32	0.49
B . .	200	107	1.16	0.45	0 85
C . .	320	107	1.97	0.65	1.39
D . .	480	107	2.6	1.02	2.0

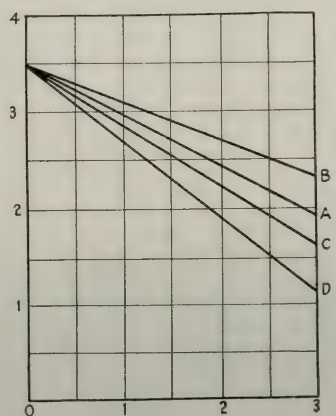

Chart E.

Chart F.—Showing the effect on the efficiency of the eye of varying the intensity of light for the semi-indirect system of lighting. Foot-candles at the point of the test card are plotted along the abscissa; loss of efficiency along the ordinate. X = points where the change in intensity was produced by changing the voltage (see Table XXI).

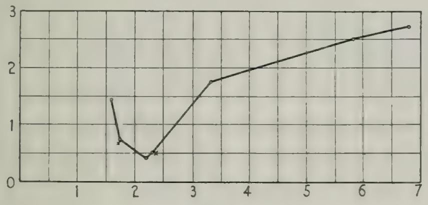

Chart F.

Chart G.—Showing the effect on the efficiency of the eye of varying the intensity of light for the direct system of lighting. Foot-candles at the point of the test card are plotted along the abscissa; and loss of efficiency along the ordinate. A = curve for 16 lamps; B, for 8 lamps.

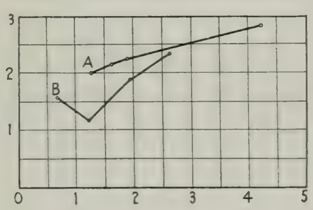

Chart G.

The results of the tests for the intensity series are shown in Tables XXI–XXIII. Three hours was selected as the period of work in all of these experiments. Briefly stated the procedure was as follows. First the most favorable intensity was determined and then variations were made on either side of this intensity until it was certain that the characteristic effect of increase and decrease of illumination was obtained. Table XXI gives the results for Observer R under the semi-indirect system. Seven variations of intensity were used. These results are typical of the effect of variations of intensities for this system. Tables XXII and XXIII show the results for the direct system for the same observer. For the direct system the most favorable intensity, it will be noted, was secured with the 8-lamp system with a total wattage lower than could be gotten with the 16-lamp system, *i. e.,* a system totalling 200 watts caused the least loss of efficiency to the eye, while 240 was the smallest total of wattage that could be secured with the 16-lamp system.

Charts have been constructed also to give a graphic representation of these tables. Chart C shows the results of Table XXI; Chart D, of Table XXII; and Chart E, of Table XXIII.

In these charts loss of efficiency was plotted against time of work. In Charts F and G loss of efficiency is plotted against intensity of light in foot-candles at the point of the test card. Chart F shows the results for Table XXI; Chart G for Tables XXII and XXIII.

IV. CONCLUSION.

Two facts may be emphasized at this point. (1) Of the lighting factors that influence the welfare of the eye, those we have grouped under the heading distribution are apparently fundamental. They seem to be the most important we have yet to deal with in our search for the conditions that give us the minimum loss of efficiency and the maximum comfort in seeing. If, for example, the light is well distributed in the field of vision and there are no extremes of surface brightness, our tests seem to indicate that the eye, so far as the problem of lighting is concerned, is practically independent of intensity. That is, when the proper distribution effects are obtained, intensities high enough to give maximum discrimination of detail may be employed

without causing appreciable damage or discomfort to the eye. (2) For the kind of distribution effects given by reflectors of the type employed in our direct and semi-indirect installations, our results show that unquestionably too much light is being used for the welfare of the eye.

Before concluding our paper we wish again to state that the units we have employed were not selected as fully representative of the classes direct, semi-indirect, and indirect. Agreement in fact has not yet been reached with regard to what falls within each of these classes. The units employed were chosen rather to show the effect on the ability of the eye to maintain its efficiency for a period of work of varying the factors we have grouped under the heading distribution. We hope ultimately to determine the limits between which each of these factors may vary without damage to the eye in a selected range of lighting situations, especially the factor surface brightness. These most favorable conditions will then serve as a goal to be attained whatever principle of lighting is employed.

Our next step in this division of the work will be to determine the effect on loss in efficiency of using reflectors of different degrees of opacity when the light is distributed to the plane of work both by the direct and indirect principles of lighting. That is, reflectors of different densities: prismatic, alba, opalux, totally opaque, etc., will be used turned up and down. In each case the installation will be made with special reference to giving the best results obtainable for the particular type of unit employed; and the factors: evenness of illumination, diffuseness of light, the angle at which the light falls on the work, and the evenness of surface brightness will be varied separately in turn, and the effect on loss of efficiency will be determined. Moreover, if it is found that the factors in question can not be studied in sufficient detail in the concrete lighting situation, the work will be supplemented by more abstract investigations. The results of this series of tests should give us among other things, for example, a still better idea of what amount of brightness difference the eye is adapted to stand, and the comparative effect of different ratios of surface brightness on loss of efficiency.

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FURTHER EXPERIMENTS ON THE EFFICIENCY OF THE EYE UNDER DIFFERENT CONDITIONS OF LIGHTING.*

BY C. E. FERREE AND G. RAND.

Synopsis: This paper is a continuation of the papers presented to the Society in 1912 and 1913. It describes the completion of the plan of work outlined in the preceding papers for one set of lighting conditions for three of the tests thus far devised by one of the writers (Ferree)—namely, a test of the ability of the eye to hold its efficiency for a period of work; a test for loss of efficiency of the fixation muscles; and a test for the comparative tendency of different conditions of lighting to produce discomfort. A report is also given of some miscellaneous experiments related to the hygienic employment of the eye in which the following points are taken up: the effect of varying the area and conversely the intrinsic brightness of the ceiling spots above the reflectors of an indirect system of lighting; the effect of varying the angle at which the light falls on the work in a given lighting situation; the effect of using an opaque eye shade with dark and light linings with each of the installations of artificial lighting employed in this and the previous work; the effect on the efficiency of the fixation muscles of three hours of work under these installations; the effect of motion pictures on the eye for different distances of the observer from the projection screen; a determination of the tendency of different conditions of lighting to produce discomfort, and a comparison of the tendency of these conditions to produce discomfort and to cause loss of efficiency.

INTRODUCTION.

The present paper is the third in a series of papers presented to this Society on the subject of lighting in its relation to the eye. In the first paper of this series[1] it was pointed out that if we are to make a comparative study of the effect of different conditions of lighting on the eye, we must have a means of estimating effects. Work was described in this paper in which

* A paper read at the eighth annual convention of the Illuminating Engineering Society, Cleveland, O., September 21-24, 1914.

[1] Tests for the Efficiency of the Eye Under Different Systems of Illumination and a Preliminary Study of the Causes of Discomfort, TRANS. I. E. S., vol. VIII, 1913, pp. 40-60.

the tests already known to physiological optics had been applied to the problem with negative results. New tests were proposed and brief results were given to show their feasibility for the problem in hand and to some extent their sensitivity. The suggestion was made that a systematic investigation of the effect of different conditions of lighting on the eye should include a study of the following points: (1) the efficiency of the fresh eye, (2) the loss of efficiency as the result of a period of work, and (3) the tendency to produce discomfort. In the second paper of the series,[2] presented to the Society last year, a plan of work was outlined and in part carried out in which the first two of the above points were covered for a given set of lighting conditions. The following factors of importance to the eye were enumerated: the evenness of illumination, the diffuseness of light, the angle at which the light falls on the object viewed, the evenness of surface brightness, intensity and quality. The first four of these factors are very closely interrelated and are apt to vary together in a concrete lighting situation, although not in a 1 : 1 ratio. It was convenient, therefore, for the purpose of this first investigation, which was primarily explorative in character, to group them together under one heading and to refer to them as distribution factors. In order to investigate the effect of certain wide variations in these factors, tests were conducted under four types of lighting in common use: one was the lighting of a room by daylight from windows; the others were the lighting of the same room by units commonly called direct, semi-indirect, and indirect, selected to serve the purposes of the test.[3]

[2] "The Efficiency of the Eye Under Different Conditions of Lighting—The Effect of Varying the Distribution Factors and Intensity." TRANS. of the Ill. Eng. Soc., 1915, vol. X, pp. 407-447.

[3] According to the plan as the investigation proceeds, the effect of varying each of these factors separately will be studied. No especial attempt was made to do this in the previous study. In making the experimental variations necessary to the investigation, it was stated as our purpose to keep as close as possible to actual lighting situations. More abstract investigations will be resorted to only when it becomes necessary to supplement the results by details that cannot be gotten from the concrete investigation. The objection to the abstract type of investigation, as the writers see the case at the present time, is that its results are very apt to be misleading. That is, what is permissible with regard to one factor in isolation, may not be at all permissible in conjunction with other factors. A more feasible plan seems to us to be to vary the factor over a certain practical range in actual concrete situations. By a proper selection of the proper situations employed, the ground of all that is practicable in lighting may be covered, and the results obtained can have a safe application.

For the systems of artificial lighting the tests were made at four positions in the room; one at which six of the eight lighting units employed were in the field of view, one at which four were in the field of view, one at which two were in the field of view, and one at which none was in the field of view. This variation of position at which the observation was made accomplishes, it was pointed out, two purposes. (1) It gives a more representative idea of the difference in the effect on the eye of the four types of lighting employed. And (2) it shows the effect of varying the number of surfaces in the field of view presenting brightness differences, more particularly the number of primary sources. The effect of varying intensity under each of the above conditions of distribution was also tested. The two sets of experiments were called respectively the distribution and intensity series. Results were given in the preceding paper for only one of the above positions in the distribution series, and for only the direct and semi-indirect systems for the intensity series. The results of the remainder of these two series of experiments, together with the report of some miscellaneous experiments will constitute the subject matter of the present paper. In these miscellaneous experiments, the following points have been taken up: the effect of varying the area and conversely the intrinsic brightness of the ceiling spots above the reflectors for the indirect system; the effect of varying the angle at which the light falls on the work; the effect of using an eye shade with dark and light linings with each of the three installations of artificial lighting; the effect on the efficiency of the fixation muscles of the eye of three hours of work under each of the conditions of lighting described in the distribution and intensity series; the effect of motion pictures on the eye for different distances of the observer from the projection screen; a determination of the tendency of each of the conditions of lighting that have been used in these experiments to produce discomfort, and a comparison of the tendency to produce discomfort and to cause loss of efficiency. Besides including some additional matter, these experiments, in connection with those of the preceding paper, complete the plan of work we had outlined for one set of lighting conditions for three of the tests we have thus far devised, namely, a test

for the ability of the eye to hold its efficiency for clear seeing for a period of work, a test for loss of efficiency of the fixation muscles, and a test for the comparative tendency of the different conditions of lighting to produce discomfort, with the exception that in a further analysis of the loss of efficiency caused by these lighting conditions, which will be carried out in part by means of these tests, data will be added later to show still more clearly the relative amounts of loss that are sustained by the different functions of the visual apparatus.

DISTRIBUTION SERIES.

As was pointed out in the former paper, in order to get the effect of variation in the distribution factors on the eye's loss of efficiency as the result of a period of work, the test should be conducted with the quality and intensity of light made as nearly equal as possible. The quality of light was made approximately the same for the three installations of artificial lighting employed by using clear tungsten lamps in each case. It was decided to make the intensity of light as nearly equal[4] as possible at the point of test, and to give a supplementary specification of the lighting effects in the remainder of the room for the three installations of artificial light.

At the point of test the light was photometered[5] in several directions. It was made approximately equal in the plane of the test card and as nearly as possible equal in the other directions. The specification of the lighting effects in the remainder of the room was accomplished as follows: (1) A determination was made of the average illumination of the room under each of the three installations. The room was laid out in 3-ft. (0.9 m.)

[4] This equalization was made at the point of test for the position of the observer with six of the fixtures in the field of view. For the other positions illumination measurements were made in several directions at the test card, and brightness measurements were made of the surface of the test card and of the observer's book held in the horizontal and 45 deg. positions. Equalization could not have been made at all of these points without having changed the relation and magnitude of the distribution factors, which would not have been in accord with the purpose of the test, namely, to determine the effect of a certain grouping or relation of these factors for the four positions in the room.

[5] We have not as yet made the fuller photometric specifications of the room lighted by daylight with our present arrangement of windows, curtains, etc. We hope to make the effect of distribution factors in daylight illumination (employing windows, skylights, etc.) the subject of a future study. In this study a photometric analysis of the illumination effects produced will be made an especial feature.

squares and illumination measurements were made at 66 of the intersections of the sides of these squares. Readings were taken in a plane 122 cm. above the floor with the receiving test plate of the illuminometer in the horizontal, the 45 deg. and 90 deg. positions measuring respectively the vertical, the 45 deg., and horizontal components of illumination. The 122 cm. plane was chosen because that was the height of the test object. (2) A determination was made of the brightness of prominent objects in the room, such as the test card, the reflectors for the semi-indirect installation, the reading page, the specular reflection from surfaces, etc. The brightness measurements were made by means of a Sharp-Millar illuminometer with the receiving test plate removed. The instrument was calibrated against a magnesium oxide surface obtained by depositing the oxide from the burning metal on a white card. By this method the reflecting surfaces were used as detached test plates. The readings were converted into candle-power per sq. in. by the following formula:

$$\text{Brightness} = \text{Foot-candles}/\pi \times 144.$$

(3) Photographs were made of the room from three positions under each system of illumination.

A complete specification of the test room, the types of installation used, and the illumination effects produced for the systems of lighting, is given in the previous paper which appears elsewhere in this number of the TRANSACTIONS (pp. 413-422). Only such data will be repeated here as are necessary for reference.[7]

In Fig. 1 the test room is shown drawn to scale: plan of room, north, south, east and west elevations. In the drawing, plan of room, are shown the 66 stations at which the illumination measurements were made, and the positions of the outlets for the lighting fixtures, A, B, C, D, E, F, G, and H. In the drawing, east elevation, the observer in position at one of the points (Position I) at which the tests were taken is repre-

[7] For a description of the *test* see the previous article referred to above (pp. 410-413); also Tests for the Efficiency of the Eye Under Different Systems of Illumination and a Preliminary Study of the Causes of Discomfort, TRANS. I. E. S., vol. VIII (1913), pp. 41-51.

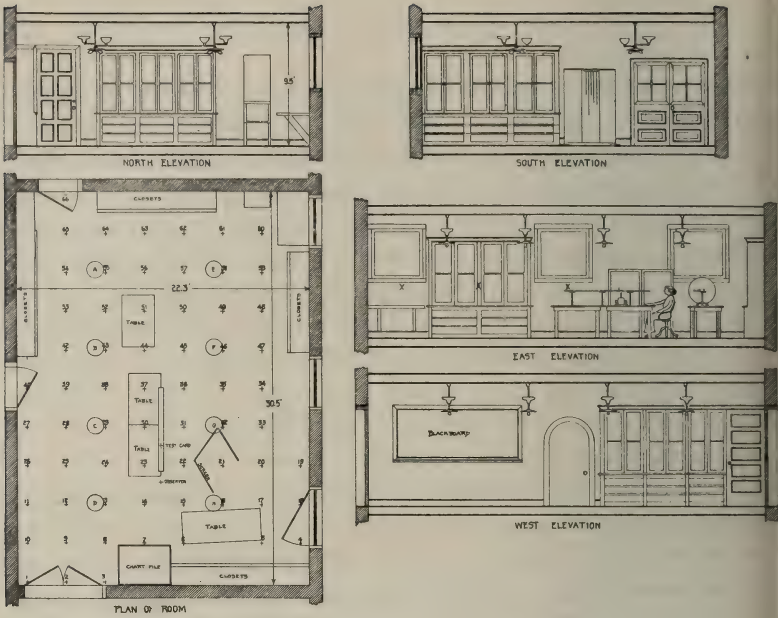

Fig. 1.—Plan of test room.

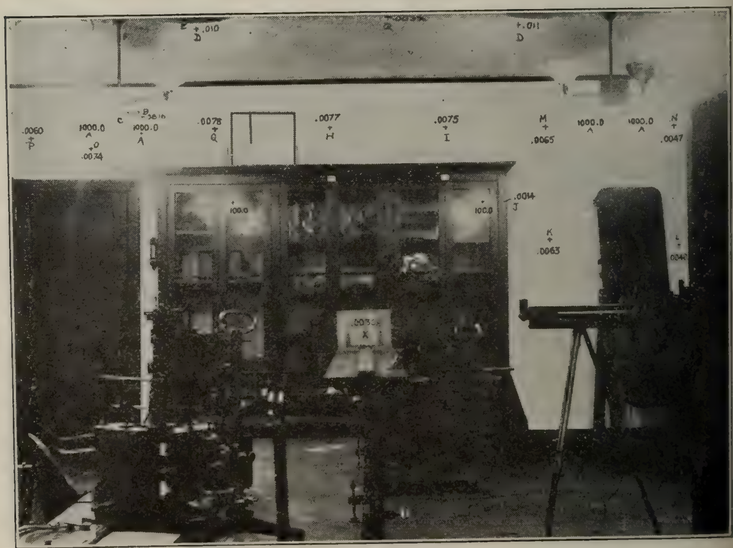

Fig. 2.—Showing brightness measurements of all surfaces having very high or very low brilliancy, direct system. The brightness of the printed page from which the observer read was, when held in the horizontal position, 0.0057 cp. per sq. in.; in the 45 deg. position, 0.004 cp. per sq. in.[6]

[6] The bright spots on the doors of the apparatus case rated at 100 cp. per sq. in., shown in Fig. 2, were not in the field of view when the tests were taken. That is, when the tests were taken, the doors were thrown open, and all of the apparatus which might give specular reflection was removed.

Fig. 3.—Showing brightness measurements of all surfaces having very high or very low brilliancy, semi-indirect system. The brightness of the printed page from which the observer read was, when held in the horizontal position, 0.0058 cp. per sq. in.; in the 45 deg. position, 0.0039 cp. per sq. in.

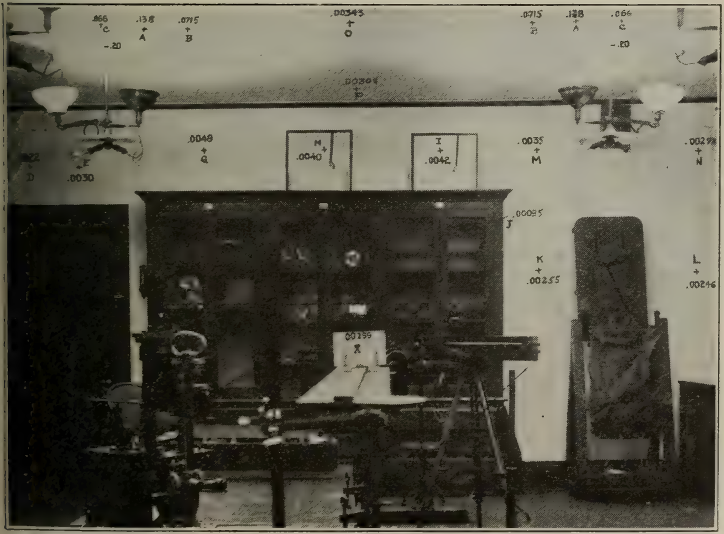

Fig. 4.—Showing brightness measurements of all surfaces having very high or very low brilliancy, indirect system. The brightness of the printed page from which the observer read was, when held in the horizontal position, 0.0088 cp. per sq. in.; in the 45 deg. position, 0.0043 cp. per sq. in.

sented.[8] The other three positions are indicated in the photographs by (x). They will be referred to in the tables and charts, in order, by the numerals II, III, and IV.

Table I shows the number and wattage of the lamps used at the outlets A, B, C, D, E, F, G, and H; and Table II shows the illumination measurements for each of the 66 stations represented in Fig. I. These measurements were made with the receiving test plate of the photometer in the horizontal, vertical and 45 deg. planes.[9]

[8] The track along which the test card was moved was parallel to the east and west walls of the room. During the three hours of reading which intervened between the two tests, the observer moved just far enough back from the upright supporting the mouth-board to give room for the book to be held and to permit of a comfortable reading position. The book was elevated and held approximately at an angle of 45 deg. When taking the test, the observer faced the north wall of the room, in such a position that with the eyes in the primary position, the lines of regard were parallel with the east and west walls of the room. Care was taken to have print of uniform size and distinctness for use with the three systems and to have a page which gave a comparatively small amount of specular reflection.

[9] See also Table III, The Efficiency of the Eye Under Different Conditions of Lighting, etc., TRANS. I. E. S., vol. X, 1915, p. 416a. This table was compiled as a supplement to Table II for the purpose of making a comparative showing of the evenness of illumination at the 122 cm. level given by the three systems of lighting. Two cases were made of this. (1) Comparisons were made of each component from station to station; (2) the difference between the components was compared. To facilitate these comparisons (a) the mean variation from the average of each of the components was computed; and (b) the difference between the averages of the three components was determined. The evenness of the illumination, it will be remembered, is not only of importance to the efficiency of the eye with reference to the object directly viewed; but also in its influence on the distribution of surface brightness. The evenness of surface brightness depends in general upon two sets of factors; (1) the nature and position of the reflecting surfaces in the room; and (2) the type of delivery of light to these surfaces.

We realize that the evenness of the illumination on the 122 cm. plane given by the indirect and semi-indirect units was somewhat interfered with by the reflectors of the direct system which were beneath and a little to the right of these units when in position for the test. Also the evenness of surface brightness on the ceiling for the direct system was interfered with by the indirect and semi-indirect reflectors which were above and a little to the side of the direct units. The influence of this "dead apparatus" will be eliminated in the next series of installations. Moreover, the installation in each case was not such as to give the best effects obtainable from the type of reflector used. For example, the indirect reflectors were too close to the ceiling to give the maximum evenness of illumination and surface brightness for the type of reflector employed. The analysis of the effects given in the former paper was not made, therefore, for the purpose of drawing general conclusions with regard to the type of reflector used. It was made solely for the sake of the comparison of the illumination effects obtained with the corresponding results for loss of efficiency.

TABLE I.

Showing the number and wattage of the lamps used at outlets A, B, C, D, E, F, G and H.

Outlet	Direct Watts	Semi-indirect Watts	Indirect Watts
A	2–60	1–100	1–100
B	2–60	1–100	1–100
C	2–60	1–100	1–100
D	2–40	1–100	1–100
E	2–60	1–100	1–100
F	2–60	1–100	1–100
G	2–60	1–100	1–100
H	2–40	1– 60	1–100

TABLE II.—DISTRIBUTION SERIES.[10]

Showing the illumination measurements in foot-candles for each of the 66 stations represented in Fig. 1 for the direct, semi-indirect, and indirect systems used.

	Horizontal			Vertical			45°		
Station	Direct	Semi-indirect	Indirect	Direct	Semi-indirect	Indirect	Direct	Semi-indirect	Indirect
1	1.41	1.44	1.22						
2	1.32	1.47	1.26						
3	1.10	1.40	1.32						
4	1.37	1.10	1.47						
5	2.03	2.58	2.20						
6	2.50	3.20	2.95						
7	2.51	3.60	2.90						
8	3.30	3.75	3.00						
9	2.78	2.53	2.20						
10	1.50	1.59	1.35						
11	2.12	1.64	1.66						
12	4.20	2.65	2.70	0.47	0.48	0.47	2.40	1.25	1.43
13	6.10	5.25	4.10	0.47	0.48	0.42	3.30	2.25	1.96
14	3.70	4.95	4.40	0.48	0.47	0.47	2.00	2.40	2.30
15	3.00	4.85	4.50	0.44	0.48	0.47	1.97	1.88	2.30
16	6.60	4.25	4.10	0.70	0.37	0.48	3.58	1.60	2.10
17	4.65	2.35	3.15	0.48	0.24	0.46	1.80	0.69	1.60
18	2.15	1.69	2.20	0.49	0.38	0.47	1.10	0.66	1.63
19	2.95	2.10	2.50						
20	5.30	3.20	3.40	1.62	0.53	0.86	3.00	2.30	2.20
21	6.60	4.80	4.60	2.00	0.71	0.94	3.60	1.85	3.00
22	2.25	4.40	4.80	0.61	0.69	1.07	1.15	1.80	2.90
23	4.50	6.00	5.10	1.20	1.14	1.10	2.18	3.30	2.90
24	6.95	5.40	5.00	1.76	1.30	1.04	3.60	3.10	3.00
25	4.85	3.72	3.50	1.33	0.78	0.75	2.75	1.85	2.10
26	2.50	1.82	2.20						
27	2.81	2.05	2.40						
28	6.50	3.28	3.70	1.30	1.11	1.12	4.40	2.10	2.50
29	9.00	6.40	5.20	1.45	1.50	1.48	6.30	3.60	3.40
30	4.95	6.95	5.40	1.36	1.46	1.40	3.15	4.15	3.60
31	4.80	6.20	5.20	0.77	1.20	1.24	2.78	3.85	3.60

TABLE II.—DISTRIBUTION SERIES.—(*Continued.*)

Station	Horizontal			Vertical			45°		
	Direct	Semi-indirect	Indirect	Direct	Semi-indirect	Indirect	Direct	Semi-indirect	Indirect
32	9.20	5.50	5.00	0.47	0.28	1.33	5.20	2.25	3.40
33	6.20	3.18	3.70	1.54	0.75	1.22	4.60	1.83	2.60
34	5.75	4.30	4.00	2.85	1.20	1.46	4.30	2.92	3.10
35	8.00	6.90	5.40	3.70	1.70	1.65	6.00	4.40	4.90
36	5.60	7.25	5.30	2.35	1.91	1.65	4.20	4.68	4.00
37	5.45	7.00	5.80	2.18	2.15	1.82	3.78	4.55	4.00
38	8.25	6.80	5.40	3.60	2.20	1.72	6.00	4.60	3.80
39	6.35	3.70	4.00	2.80	1.40	1.43	4.60	2.80	3.00
40	3.00	2.05	2.30						
41	2.70	1.73	2.10						
42	7.30	3.65	3.50	2.50	1.64	1.36	5.40	2.93	2.80
43	9.80	6.90	5.00	2.70	2.08	1.78	7.20	4.50	3.90
44	5.50	7.10	5.20	2.42	2.18	1.88	4.35	5.10	4.30
45	5.45	8.00	5.20	2.60	2.00	1.93	4.80	5.30	4.20
46	10.00	7.70	5.20	2.75	1.90	1.86	8.00	5.40	4.10
47	6.60	4.20	3.60	2.45	1.56	1.33	5.30	3.05	2.90
48	5.80	4.35	3.70	3.20	1.69	1.74	5.00	3.60	3.30
49	8.40	7.20	4.80	4.30	2.55	2.10	7.20	5.80	4.00
50	5.50	7.70	4.90	3.35	2.42	2.10	8.50	5.80	4.10
51	5.40	6.80	5.00	3.05	2.68	2.15	4.60	5.35	4.35
52	8.00	6.40	4.70	4.20	2.55	1.93	6.50	4.82	4.00
53	6.60	3.85	3.60	3.00	1.77	1.41	5.00	3.20	3.00
54	6.95	2.88	2.80	2.62	1.80	1.50	5.80	3.00	2.90
55	9.00	5.90	3.90	3.15	2.40	1.94	8.00	5.20	3.75
56	4.95	5.90	4.60	3.15	2.50	2.10	5.30	5.80	4.40
57	4.65	6.10	4.50	3.00	2.60	2.20	4.65	5.80	4.40
58	9.75	6.35	4.00	3.35	2.58	2.00	8.50	5.80	4.00
59	5.85	3.20	2.90	2.98	1.90	1.76	5.60	3.62	3.10
60	3.85	2.57	2.60			1.66			2.90
61	5.20	4.20	3.10	4.45	2.60	1.90	7.80	5.40	3.50
62	3.30	4.20	3.20	3.30	2.95	2.10	4.95	5.70	3.70
63	3.52	4.20	3.00	3.60	2.80	2.20	5.60	5.00	3.50
64	5.40	3.70	3.10	4.60	2.45	1.93	7.65	4.60	3.40
65	4.15	2.40	2.25	4.00	1.79	1.54	5.50	2.82	2.60
66	2.10	1.42	1.35						
Average	5.0	4.27	3.61	2.32	1.59	1.48	4.77	3.63	3.30

[10] Reduced to equal wattages (800 watts) these installations give the following average illumination values in foot-candles for the receiving test plate in the positions specified above: Direct system: horizontal, 4.54; vertical, 2.2; 45°, 4.33. Semi-indirect system horizontal, 4.49; vertical, 1.67; 45°, 3.82. Indirect: horizontal, 3.61; vertical, 1.48; 45°, 3.3

It may not be out of place to suggest here that a careful study of the illuminating efficiency of different types of lighting units should be made under conditions that are strictly comparable for a wide range of variation. Such tests should be made under common supervision in a model room so constructed as readily to permit of the kind of variations needed; and should be, if possible, paralleled by tests for the efficiency of the eye. In working towards a reconstruction of lighting conditions, it is obvious that tests for the efficiency of the eye and for illuminating efficiency should go hand in hand.

Figs. 2, 3 and 4 are taken from the series of 9 photographs (see Figs. 2-10, op. cit., pp. 416b-416d) showing the illumination effects produced by the three systems of lighting. In these figures are given the brightness measurements of all surfaces having very high or very low brilliancy. The spot measured is indicated by a cross and the numerical value of the brightness measurement in candlepower per square inch is printed nearby. These spots are also lettered for convenience of reference in the intensity series. That is, since several installations were used in the intensity series, it was found convenient to express these values in tabular form and to identify them with the surfaces measured by means of letters. These photographs were taken from a point in line with the four positions of the observer as near to the south wall of the room as was possible; but owing to the narrow field of the camera as compared with the binocular field, these views include, for example, only about one-half of the field of vision of the observer at the test station nearest to this wall of the room. The camera's field in this position corresponds in fact very closely to the field presented to the observer seated at the center of the room. While, therefore, not all of his field of view for all of the positions at which tests were made is covered by the brightness measurements shown in the photographs, still the order of brightness difference present in the field of view for the different systems is well represented by these measurements, as can be seen by an inspection of the preceding photographs (see also Figs. 2-10, op. cit., pp. 416b-416d) and from the descriptions of the installations used. In order to facilitate certain features of comparison such as, for example, the evenness of surface brightness for each system for all of the room; for all of the room but the sources of light; and for all of the room but the sources and the spots above the sources, the brightness measurements shown in Figs. 2, 3 and 4 are also given in tabular form. These measurements and the letters identifying them with the surfaces measured, are given in Table III. In making the comparison it should be noted that the spots mentioned are not in all cases identical for the three systems. That is, owing to the different effects produced by the different reflectors, the same spots were not always conspicuously light or dark for the three systems. The letters, E,

F, G, etc., may then refer to entirely different spots in case of the three systems.

TABLE III.—DISTRIBUTION SERIES.

Showing the brightness measurements in candlepower per square inch for the surfaces A, B, C, D., etc., see Figs. 2, 3 and 4.

Surface measured	Direct system	Semi-indirect system	Indirect system
A	1000.0000	0.710	0.138
B	0.3816	0.057	0.0715
C	0.517	0.093	0.066
D	0.010	0.059	0.0022
E	0.00296	0.0029	0.0030
F	0.0044	0.0033	0.00123
G	0.0078	0.0053	0.0049
H	0.0077	0.006	0.0040
I	0.0075	0.0062	0.0042
J	0.0014	0.0010	0.00095
K	0.0063	0.0046	0.00255
L	0.0042	0.0027	0.00246
M	0.0065	0.0051	0.00352
N	0.0047	0.0027	0.00272
O	0.0074	0.0066	0.00343
P	0.006	0.00484	0.00308
Q	0.00396		

TABLE IV.—DISTRIBUTION SERIES.

Showing the brightness measurements in candlepower per sq. in. of the test card, reading page horizontal, and reading page in the 45 deg. position for Positions I, II, III, and IV, for the direct, semi-indirect, and indirect systems.

Position of observer	Surface measured	Direct system	Semi-indirect system	Indirect system
I	Test card	0.00308	0.0030	0.00299
	Reading page horizontal	0.0057	0.0058	0.0088
	Reading page 45° position	0.004	0.0039	0.00431
II	Test card	0.00506	0.00453	0.0046
	Reading page horizontal	0.0088	0.0107	0.0088
	Reading page 45° position	0.0068	0 00726	0.00792
III	Test card	0.0055	0.00462	0.00453
	Reading page horizontal	0.0092	0.0087	0.00814
	Reading page 45° position	0.00704	0.0077	0.00594
IV	Test card	0.0066	0.00475	0.00453
	Reading page horizontal	0.00814	0.00572	0.00572
	Reading page 45° position	0.0063	0 00484	0.00484

In Table IV are given the brightness measurements in candlepower per square inch for the test card and the reading page for the four positions of the observer: I, II, III and IV, for the direct, semi-indirect and indirect systems. The measurements of the reading page were taken at the point of work for the four positions of the observer with the book in the horizontal and 45 deg. position. During work the book was held in the 45 deg. position.

In Tables V and VI are shown some prominent ratios of sur-

face brightness for the three systems.[11] (See also Table VIII, op. cit., p. 421.)[12]

In compiling these ratios it has been considered important to make a comparative showing for the three systems (a) of the extremes of surface brightness; and (b) of the relation of the brilliancy of objects in the surrounding field to the surface brightness at the point of work. The extremes of surface brightness

[11] In attempting to make comparisons of the effect of the different magnitudes of brightness ratios, one obviously must bear in mind that the surfaces between which the ratios are established are not in all cases in the same position in the field of vision for the three systems. For example, the brightest surfaces in case of the indirect system, namely, the spots on the ceiling directly above the reflectors, are farther removed from the direct line of vision of the observer in the working position than were the brightest surfaces in case of the direct and semi-indirect systems. The position of the surface in the field of vision would come into question, for example, in making a determination of the maximum value of brightness difference the eye is adapted to stand. While we have done a great deal of work on the effect of position of the brilliant surface in the field of vision in our investigation of the causes of discomfort, we have made no especial investigation of this point in relation to loss of efficiency. Doubtless what we shall all have to bear in mind is that, even in the end, we cannot hope to specify narrowly what is most favorable, etc. In lighting conditions. The factors that enter into the concrete lighting situation are so complex or rather are so variable and so rarely duplicated that we can hope to make general specifications with regard to what is most favorable, for example, only within very broad limits. If one wishes to work the conditions down to a finer point than this, the particular installation must be tested *in situ*. We are at present working on a test which we hope will serve this purpose better than the test which has been used in the work described in the preceding papers.

[12] Table VIII, (op. cit., p. 421) was compiled from Tables IV-VII of that paper to show the mean variation in surface brightness for all the surfaces measured for the direct, semi-indirect, and indirect systems. In referring back to that paper it may not be out of place to call to mind again that the percentages given in Table VIII seem to indicate that the great advantage of the indirect over the other systems of lighting we have used with regard to the factor, evenness of surface brightness, comes, primarily at least, from its provisions for shielding the eye from the light source rather than from any conspicuously greater evenness of illumination given by it to the objects in the field of view. In fact, as may be seen from that table, all the systems give a fairly even distribution of surface brightness outside of the source and the surfaces immediately surrounding it.

The need of keeping surface brightness within certain limits and the primary importance of properly shielding the eye from the source, to the accomplishment of this desideratum, are obvious. Doubtless many ways will be devised in course of time for cutting down useless and harmful brightness differences in lighting effects. For example, the possibility is here suggested of producing a still smaller brightness difference than is given by the indirect reflectors of the type we have employed, by using semi-indirect reflectors of such a density as to give a surface brilliancy equal to that of the spot of light cast upon the ceiling. The value of this brilliancy, because of the larger area of luminous surface presented, could then be made smaller than that of the ceiling spot cast by the indirect reflector and still give the same amount of light to the room. A similar effect may be obtained with the indirect reflector by using lamps of lesser wattage and adding the light needed to make up the deficiency by installing directly beneath the reflector lamps of low wattage in translucent enclosures of a density that gives a surface brilliancy equal to that of the ceiling spots. The effect of both of these devices would be to lower the surface brilliancy for a given light flux by increasing the area of the luminous surface. Whether either device would be advisable from other standpoints we are not at present prepared to say.

are shown by giving the ratios between surfaces of the first, second, third, etc., order of brilliancy and the surface of the lowest order of brilliancy; and the comparison of the brilliancy of objects in the surrounding field to the brightness at the point of work by giving the ratios of the surfaces of the first, second, and third order of brilliancy to the brightness of the test card and the reading page in the working position. The following points may be noted. (1) The illumination effects produced by the direct system are characterized by great extremes of surface brightness, and a high ratio of brilliancy of objects in the surrounding field to the surface brightness at the point of work. These effects are much less pronounced for the semi-indirect system and still less for the indirect. (2) A comparison of this table with the tables giving loss of efficiency as the result of work shows that while the extremes of surface brightness are enormously larger for the direct than for the semi-indirect system, the eye loses almost as much in efficiency for three hours of work under the semi-indirect as under the direct system. That is, the greatest ratio of brightness for the direct system is over one thousand times as much as the greatest ratio for the semi-indirect, while the difference in loss of efficiency for the two systems is comparatively insignificant. On the other hand, the greatest ratio of brightness for the semi-indirect system is only about five times as much as for the indirect; while the difference in loss of efficiency for three hours of work is very large, this loss of efficiency for three hours of work for the indirect system being, it will be noted, very small indeed. This seems to indicate (a) that for the scale of brightness magnitudes and the illumination effects present in this series of experiments the gradation of surface brightness for the indirect system is very close to what the eye is adapted to stand without loss of efficiency; and (b) that an increase in difference in brightness above this point is followed at first by a rapid increase in loss of efficiency and later by a much slower increase. In the intensity series, in the work of the former paper, it will be remembered, the following points also came out. (1) The effect of size of ratio on loss of efficiency is different for different orders of magnitude of brightness. And (2) the size of the brilliant object, as

well as its brilliancy, is of importance. That is, within certain limits, as yet undefined, an increase in the area of the brilliant surface causes an increase in loss of efficiency.

In Table V the ratios were compiled from measurements showing the extremes of brightness of prominent surfaces in the room. In Table VI they were compiled to show the relation of the brilliancy of objects in the surrounding field to the surface brightness at the point of work for the positions of the observer, I, II, III and IV[13] (see Fig. 1, p. 452a). In general a falling off in the magnitude of brightness differences in the field of view will be noted in order from the Positions I to IV. This falling off is greatest for the direct system, next greatest for the semi-indirect, and least for the indirect. Thus there is not only a decrease in the number of surfaces in the field of view showing a high brilliancy from Positions I to IV, but also a decrease in the magnitude of brightness difference between the surfaces of high brilliancy and the test card, between these surfaces and the reading page, etc., especially for the direct and semi-indirect systems. An inspection of the table for loss of efficiency shows, roughly speaking, a correspondingly marked decrease in loss of efficiency from Positions I to IV for the systems which show the marked decrease in brightness difference, that is, for the direct and semi-indirect systems. The decrease in loss of efficiency, it will be noted, is practically nothing for the indirect system. Thus not only much less loss of efficiency is sustained by the eye for the indirect units used, but the results are much more independent of the position of the observer in the room.

The loss of efficiency for the Positions I, II, III and IV for the three systems is shown in Table VII.[14]

[13] It may also be of interest to the reader to work out for these four positions the ratios: lightest to darkest, darkest to test card, darkest to reading page, etc.

[14] Obviously in the consideration of the effect of a given lighting situation on the ability of the eye to hold its efficiency for a period of work, the age of the observer and the condition of his eyes should be taken into account. All the observers that have been employed by us in this work were under 26 years of age. Following is a clinic report of the eyes of the observer whose results are given in the following table, made by Dr. Wm. Campbell Posey of Philadelphia.

Observer R.

With glasses.—Vision of right eye = 20/25. Far muscle test = O ½ esophoria.
Vision of left eye = 20/20- Near muscle test = orthophoria.

Ophthalmoscopic examination.—Right eye = mixed astigmatism, ½ diopter.
Left eye = hyperopic astigmatism, 1½ diopters.

(*Continued on next page.*)

Chart I gives a graphic representation of the results of this table. Loss of efficiency is plotted along the ordinate and time of work along the abscissa. Each of the large squares along the abscissa represents an hour of work and along the ordinate an integer of the ratio, time clear to time blurred. The effect on loss of efficiency of the number and magnitude of brightness of surfaces of high brilliancy, especially of primary sources, in the field of view is obvious from these charts. The chart for position IV, however, shows that there is still a considerable difference in the loss of efficiency produced by the three systems, even when there are no sources or other surfaces of high brilliancy in the field of view. The indirect system still gives the least loss of efficiency, the semi-indirect next, and the direct the most. As may be seen in Figs. 2, 3, and 4, and in Tables III and VI there was little difference in the evenness of surface brightness in the field of view presented to the observer in this position, certainly none that could be considered of consequence in favor of the indirect system. The above results seem to indicate, therefore, that while the evenness of surface brightness is an important factor it is not the only factor in a lighting situation which may influence the amount of loss of efficiency sustained by the eye as the result of a period of work

We wish to repeat in this paper what was very strongly emphasized in our former paper, namely, that the units we have employed were not selected as fully representative of the classes direct, semi-indirect, and indirect. Agreement in fact has not yet been reached with regard to what falls within each of these

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External condition.—Adduction good; eyes slightly divergent under cover; cornea clear; pupils, 2½ mm.; irides respond equally and freely to light, accommodation, and convergence stimuli.

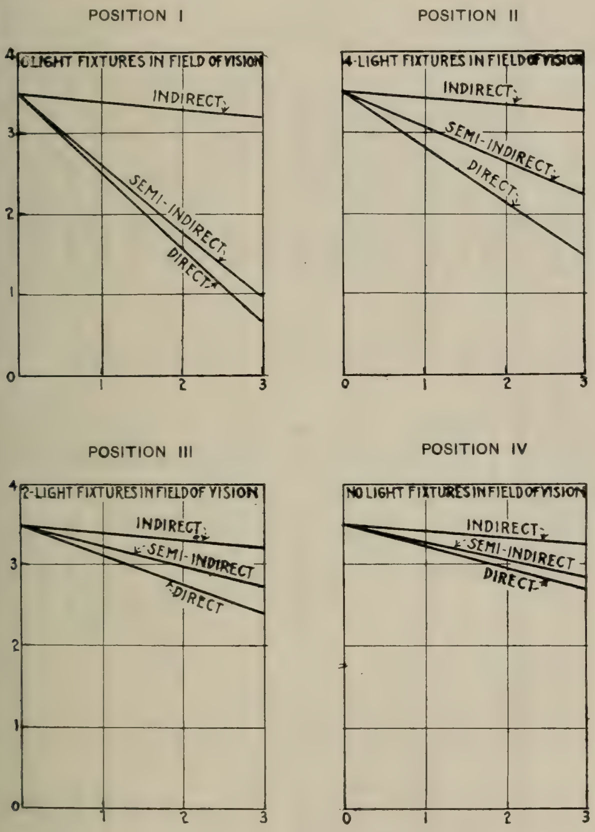
Glasses worn during test.—Right eye = —S., 0.50 D.;—C., 0.37D., x 160°
Left eye = —C., 0.50 D., x 180°

Lest the former paper has not appeared in print before this one is presented it may be well to make some mention here also of the reproducibility of results that may be obtained for our test for loss of efficiency. The mean variation of the ratio, time clear to time blurred for the same observer working under conditions as nearly constant as possible, is very small indeed. The order of magnitude of the mean variation of the test for the fresh eye was obtained as follows. Beginning at 9 A. M. five 3 minute tests were run with a rest period of 20 minutes between each test This was done with all observers on several days under each system of lighting employed. The rest period was taken in each case in a room lighted by daylight, with the observer facing a wall with an evenly lighted matt surface. For a single series of five tests the variation in the time seen clear in the 3 minute periods have always fallen within 1 per cent. for all of the observers we have used and for all systems of lighting.

classes. The units employed were chosen rather to show the effect of varying the factors we have grouped under the heading of distribution on the ability of the eye to maintain its efficiency for a period of work. We hope ultimately to determine the

CHART I.—DISTRIBUTION SERIES.

Showing the effect on loss of efficiency of varying the observer's position in the room, or the number of bright sources, primary and secondary, in the field of vision.



limits between which each of these factors may vary in a selected range of lighting situations, without damage to the eye, especially the factor surface brightness. These most favorable conditions will then serve as a goal to be attained whatever principal of lighting is employed.

TABLE V.—DISTRIBUTION SERIES.

Ratios showing the extremes of surface brightness for the direct, semi-direct, and indirect systems used.

Ratio	Direct system	Semi-indirect system	Indirect system
Lightest to darkest...............	1000/0.0014 = 714,285	0.710 /0.001 = 710	0.138 /0.00095 = 145
2nd lightest to darkest......	0.3816/0.0014 = 123.9	0.093 /0.001 = 93.0	0.0715 /0 00095 = 75.2
3rd lightest to darkest.............	0.0517/0.0014 = 37.0	0.059 /0.001 = 59.0	0.066 /0.00095 = 69.4
4th lightest to darkest	0.01 /0.0014 = 7.14	0.057 /0.001 = 57.0	0.0049 0/.00095 = 5.15
5th lightest to darkest	0.0078/0.0014 = 5.57	0.0066 /0.001 = 6.6	0.0042 /0.00095 = 4.42
6th lightest to darkest	0.0077/0.0014 = 5.50	0.0062 /0.001 = 6.2	0.0040 /0.00095 = 4.21
7th lightest to darkest	0.0075/0.0014 = 5.35	0.0060 /0.001 = 6.0	0.00352/0.00095 = 3.70
8th lightest to darkest	0.0074/0.0014 = 5.28	0.0053 /0.001 = 5.3	0.00343/0.00095 = 3.61
9th lightest to darkest	0.0065/0.0014 = 4.64	0.0051 /0.001 = 5.1	0.00308/0.00095 = 3.24
10th lightest to darkest	0.0063/0.0014 = 4.5	0.00484/0.001 = 4.84	0.0030 /0.00095 = 3.15
11th lightest to darkest	0.006 /0.0014 = 4.28	0.0046 /0.001 = 4.6	0.00255/0.00095 = 2.68
12th lightest to darkest	0.0047/0.0014 = 3.36	0.0033 /0.001 = 3.3	0.00246/0.00095 = 2.57
13th lightest to darkest	0.0404/0.0014 = 3.14	0.0029 /0.001 = 2.9	0.0022 /0.00095 = 2.31
14th lightest to darkest	0.0042/0.0014 = 3.00	0.0027 0/00.1 = 2.7	0.00123/0.00095 = 1.29

TABLE VI.—DISTRIBUTION SERIES.

Ratios showing the relation of the brilliancy of objects in the surrounding field to the surface brightness at the point of work for Positions I, II, III, and IV for the direct, semi-indirect, and indirect systems used.

Position of observer	Ratio	Direct system	Semi-indirect system	Indirect system
I	Lightest to test card	1000/0.00308 = 324,674	0.710 /0.003 = 236.7	0.138 /0.00299 = 46.0
	Lightest to reading page	1000/0.004 = 250,000	0.710 /0.0039 = 182.0	0.138 /0.00431 = 32.0
	2nd lightest to test card	0.3816/0.00308 = 123.9	0.093 /0.003 = 31.0	0.0715 /0.00299 = 24.0
	2nd lightest to reading page	0.3816/0.004 = 95.3	0.093 /0.0039 = 24.0	0.0715 /0.00431 = 16.5
	3rd lightest to test card	0.0517/0.00308 = 16.8	0.059 /0.003 = 29.7	0.066 /0.00299 = 22.0
	3rd lightest to reading page	0.0517/0.004 = 12.9	0.059 /0.0039 = 15.0	0.066 /0.00431 = 15.0
II	Lightest to test card	1000/0.00506 = 197,628	0.710 /0.00453 = 156.7	0.138 /0.0046 = 30.0
	Lightest to reading page	1000/0.0068 = 147,059	0.710 /0.00726 = 97.8	0.138 /0.00792 = 17.0
	2nd lightest to test card	0.3816/0.00506 = 75.4	0.093 /0.00453 = 20.5	0.0715 /0.0046 = 15.5
	2nd lightest to reading page	0.3816/0.0068 = 56.0	0.093 /0.00726 = 12.8	0.0715 /0.00792 = 9.0
	3rd lightest to test card	0.0517/0.00506 = 10.2	0.059 /0.00453 = 13.0	0.066 /0.0046 = 14.3
	3rd lightest to reading page	0.0517/0.0068 = 7.6	0.059 /0.00726 = 8.0	0.066 /0.00792 = 8.0
III	Lightest to test card	1000/0.0055 = 181,818	0.710 /0.00462 = 154.0	0.138 /0.00453 = 30.4
	Lightest to reading page	1000/0.00704 = 142,055	0.710 /0.0077 = 92.0	0.138 /0.00594 = 23.0
	2nd lightest to test card	0.3816/0.0055 = 69.0	0.093 /0.00462 = 26.0	0.0715 /0.00453 = 15.8
	2nd lightest to reading page	0.3816/0.00704 = 54.0	0.093 /0.0077 = 12.0	0.0715 /0.00594 = 12.0
	3rd lightest to test card	0.0517/0.0055 = 9.0	0.059 /0.00462 = 12.8	0.066 /0.00453 = 12.0
	3rd lightest to reading page	0.0517/0.00704 = 0.7	0.059 /0.0077 = 7.7	0.066 /0.00594 = 11.0
IV	Lightest to test card	0.0063/0.0066 = 0.954	0.00484/0.00475 = 1.019	0.00484/0.00453 = 1.068
	Lightest to reading page	0.0066/0.0063 = 1.047	0.00475/0.00484 = 0.785	0.00453/0.00484 = 0.936
	2nd lightest to test card	0.0014/0.0066 = 0.212	0.010 /0.00475 = 0.0210	0.00095/0.00453 = 0.209
	2nd lightest to reading page	0.0014/0.0063 = 0.222	0.010 /0.00484 = 0.00207	0.00095/0.00484 = 0.196

TABLE VII.—DISTRIBUTION SERIES.

Showing the effect on loss of efficiency of varying the observer's position in the room, or the number of light sources primary and secondary, in the field of vision. At Position I, six light fixtures were in the field of vision; at Position II, four light fixtures; at Position III, two light fixtures; and at Position IV, no light fixtures.

Position of observer	Lighting system	Watts	Volts	Intensity foot-candles Horizontal	Vertical	45°	Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Total time clear ÷ total time blurred	Ratios reduced to comm. standard
I.	Indirect.....	800	107	5.2	1.36	3.5	9 A.M.	84.5	67.5	135	45	3.0	3.5
							12 M.	84.5	67.5	132	48	2.75	3.2
	Semi-indirect	760	107	5.8	1.45	4.0	9 A.M.	80.5	68.5	142	38	3.73	3.5
							12 M.	79.5	68.5	92	88	1.04	0.97
	Direct	880	107	4.2	1.41	2.6	9 A.M.	81.0	68.0	139	41	3.39	3.5
							12 M.	78.0	68.0	71	109	0.65	0.67
II.	Indirect.....	800	107	5.1	1.98	4.2	9 A.M.	86.5	74.0	141	39	3.61	3.5
							12 M.	86.5	74.0	139	41	3.39	3.28
	Semi-indirect	760	107	6.1	2.5	4.7	9 A.M.	87.0	75.0	138	42	3.28	3.5
							12 M.	87.0	75.0	123	57	2.19	2.2
	Direct	880	107	4.65	2.75	4.4	9 A.M.	87.0	75.0	134	46	2.91	3.5
							12 M.	84.0	75.0	99	81	1.22	1.46
III.	Indirect.....	800	107	3.9	2.1	4.0	9 A.M.	84.0	70.0	130	50	2.6	3.5
							12 M.	84.0	70.0	127	53	2.4	3.23
	Semi-indirect	760	107	5.0	2.6	5.4	9 A.M.	84.0	69.0	131	49	2.67	3.5
							12 M.	84.0	69.0	122	58	2.1	2.73
	Direct	880	107	4.0	2.9	4.6	9 A.M.	83.5	70.0	148	32	4.6	3.5
							12 M.	83.0	70.0	137	43	3.8	2.41
IV.	Indirect.....	800	107	2.9	2.1	3.6	9 A.M.	84.0	70.0	139	41	3.39	3.5
							12 M.	84.0	70.0	137	43	3.18	3.27
	Semi-indirect	760	107	3.4	3.0	4.4	9 A.M.	83.5	70.5	139	41	3.39	3.8
							12 M.	83.5	70.5	132	48	2.75	2.83
	Direct	880	107	3.0	3.4	4.5	9 A.M.	82.0	69.0	119	61	1.95	3.5
							12 M.	81.0	69.0	108	72	1.5	2.7

As was also stated in our former paper our next step in this division of the work will be to determine by using reflectors of different degrees of opacity the effect on loss of efficiency when the light is distributed to the plane of work both by the direct and indirect principles of lighting. That is, reflectors of different densities: prismatic, alba, opal lux, totally opaque, etc., will be used turned up and down. In each case the installation will be made with special reference to giving the best results obtainable for the particular type of unit employed; and the factors: evenness of illumination, diffuseness of light, the angle at which the light falls on the work, and the evenness of surface brightness, will be varied separately in turn and the effect on loss of efficiency will be determined. Moreover, if it is found that the factors in question cannot be studied in sufficient detail in the concrete lighting situation, the work will be supplemented by more abstract investigations. The results of this series of tests should give us among other things, for example, a still better idea of what amount of brightness difference the eye is adapted to stand, and the comparative effect of different ratios of surface brightness on loss of efficiency.

INTENSITY SERIES.

In the work of the preceding paper we had undertaken to determine the most favorable intensities for the three types of artificial lighting we had used in the distribution series, and the effect of varying intensity with the particular grouping of distribution factors represented in each case. As was stated in the introduction of the present paper, this work was completed for the direct and semi-indirect systems but not for the indirect. For the semi-indirect installation it will be remembered that the eye fell off heavily in efficiency for all intensities with the exception of a very narrow range on either side of 2.2 foot-candles, measured at the point of work with the receiving test plate of the photometer in the horizontal plane. For the direct installation no intensity could be found for which the eye did not lose a great deal in efficiency as the result of work. For the indirect installation, however, as the following data will show, a comparatively wide range of intensity may be used without the eye suffering

any considerable loss of efficiency as the result of three hours of continuous work.

The tests were made in the same room, with the same fixtures, and in general, with the same conditions of installation and methods of working as were described in the work on the distribution factors. To secure the various degrees of intensity needed, lamps of different wattage were employed. These were selected from a series of tungsten lamps ranging from 15 to 100 watts. In order to keep the distribution factors as nearly constant as possible for a given type of system, the lamps used in making the test for that type of system were all of one wattage, *i. e.*, were all 15's, 25's, 40's, 60's or 100's.

For the indirect system the total range of intensity employed is shown by the following figures. The series was begun with 25-watt lamps, and consisted of 25, 40, 60, and 100-watt lamps. For the 25 watt lamps the photometer reading at the point of work with the receiving test plate in the horizontal plane showed 1.33 foot-candles of light; with the receiving test plate in the vertical plane, 0.39 foot-candle; and with the receiving test plate in the 45 deg. plane, 0.87 foot-candle. For the 100-watt lamps 5.2 foot-candles were obtained with the receiving test plate in the horizontal plane; 1.36 foot-candles with the test plate vertical; and 3.5 foot-candles with the test plate inclined 45 deg. The tests for loss of efficiency[15] showed probably a slight advantage for the 25-watt lamps, although the difference in result for the different intensities is sufficiently near in value to the mean variation of the test as to be scarcely worthy of consideration.

As was the case for the direct and semi-indirect installations, the following specification was made of the illumination effects produced by the indirect installation. (1) Illumination measure-

[15] In conducting these tests it was found necessary to allow a period of adaptation without work, to the illumination of the room before the first test was taken. If this were not done, especially in case of the lower intensities of lights used, the changing sensitivity of the eye to the intensity of light employed, produced a noticeable change in the visual acuity between the times the tests before and after work were taken. Since the distance of the test card was kept the same for the two tests, this change in the visual acuity tended to influence the ratio, time clear to time blurred. To determine the length of time needed under a given intensity of light to insure a constant acuity, so far as adaptation is concerned, preliminary tests were made as follows. The acuity of the observer was taken every 3 minutes until no noticeable change was found. This length of time was then always allowed for that observer as an adaptation period prior to the loss of efficiency test conducted for the given intensity of illumination.

ments were made for the highest intensity employed at the 66 stations in the test room. These measurements were made in the way described in the preceding section. For the other intensities used, measurements were made at nine representative stations to show in a general way the order of magnitude of reduction produced by using the lamps of lower wattage. (2) Brightness measurements were made of the prominent objects in the room, such as the test card, the book of the observer, and all surfaces showing very high or very low brilliancy for all of the intensities.

In Table VIII are given the illumination measurements at the 66 stations for the highest wattages used, made with the receiving test plate of the photometer in the horizontal, vertical, and 45 deg. planes. Tables IX and X show the illumination measurements at the nine representative stations for the other wattages employed in the series. The order of magnitude of reduction of the illumination of the room produced by using the lamps of lower wattage conforms pretty closely in each case, it will be observed, to the simple ratio of the wattages employed. (See foot-note to Table XII, p. 472.) As was the case for the semi-indirect system, noted in the preceding paper, socket extenders had to be used with the 25 and 40-watt lamps. That is, without the extenders these lamps, owing to their smaller size, came so low in the reflector as to change the distribution effects given by reflectors. For example, without the socket extenders for these shorter lamps, the spot of light on the ceiling was made smaller and correspondingly more brilliant. It was thought advisable to determine whether this comparatively small change in illumination effects would cause any difference in the eye's ability to hold its efficiency for a period of work. In the specification of illuminating effects, therefore, measurements have been made for the 25 and 40-watt lamps both with and without socket extenders. In Table IX illumination measurements for the 25 and 40-watt lamps are given with socket extenders, and in Table X illumination measurements for these lamps are given without socket extenders. In Table XI are given the brightness measurements for the indirect installation for the different intensities used, both with and without socket extenders for the 25 and 40-watt lamps.

The points at which the measurements were taken are indicate by the letters A, B, C, D, E, F, etc., see Fig. 4, p. 452b. In Tabl XII are given the prominent brightness ratios for the differen intensities used. Obviously an important point of compariso for the purposes of this investigation is the ratios with and with out socket extenders for the 25 and 40-watt lamps.

TABLE VIII.—INTENSITY SERIES.

Showing the illumination measurements in foot-candles for each of the stations represented in Fig. 1 for the indirect system used.

Station	Horizontal	Vertical	45°	Station	Horizontal	Vertical	45°
1	1.22	—	—	34	4.0	1.46	3.1
2	1.26	—	—	35	5.4	1.65	4.9
3	1.32	—	—	36	5.3	1.65	4.0
4	1.47	—	—	37	5.8	1.82	4.0
5	2.2	·	—	38	5.4	1.72	3.8
6	2.95	—	—	39	4.0	1.43	3.0
7	2.9	—	—	40	2.3	—	—
8	3.0	—	—	41	2.1	—	—
9	2.2	—	—	42	3.5	1.36	2.8
10	1.35	—	—	43	5.0	1.78	3.9
11	1.66	—	—	44	5.2	1.88	4.3
12	2.7	0.47	1.43	45	5.2	1.93	4.2
13	4.1	0.42	1.96	46	5.2	1.86	4.1
14	4.4	0.47	2.3	47	3.6	1.33	2.9
15	4.5	0.47	2.3	48	3.7	1.74	3.3
16	4.1	0.48	2.1	49	4.8	2.1	4.0
17	3.15	0.46	1.6	50	4.9	2.1	4.1
18	2.2	0.47	1.63	51	5.0	2.15	4.35
19	2.5	—	—	52	4.7	1.93	4.0
20	3.4	0.86	2.2	53	3.6	1.41	3.0
21	4.6	0.94	3.0	54	2.8	1.5	2.9
22	4.8	1.07	2.9	55	3.9	1.94	3.75
23	5.1	1.1	2.9	56	4.6	2.1	4.4
24	5.0	1.04	3.0	57	4.5	2.2	4.4
25	3.5	0.75	2.1	58	4.0	2.0	4.0
26	2.2	—	—	59	2.9	1.76	3.1
27	2.4	—	—	60	2.6	1.66	2.9
28	3.7	1.12	2.5	61	3.1	1.9	3.5
29	5.2	1.48	3.4	62	3.2	2.1	3.7
30	5.4	1.4	3.6	63	3.0	2.2	3.5
31	5.2	1.24	3.6	64	3.1	1.93	3.4
32	5.0	1.33	3.4	65	2.25	1.54	2.6
33	3.7	1.22	2.6	66	1.35	—	—
				Average	3.61	1.48	3.3

TABLE IX.—INTENSITY SERIES.

Showing the illumination measurements in foot-candles at nine representative stations for the different intensities used for the indirect system. Socket extenders used with the 40 and 25-watt lamps.

Station	Horizontal				Vertical				45°			
	800	480	320	200	800	480	320	200	800	480	320	200
Card	5.2	3.0	1.7	1.33	1.36	0.765	0.49	0.39	3.5	1.97	1.08	0.87
12	2.7	1.63	0.97	0.65	0.47	0.265	0.18	0.12	1.43	0.83	0.48	0.44
16	4.1	2.2	1.32	1.11	0.52	0.33	0.24	0.14	2.1	1.22	0.66	0.6
31	5.2	2.7	1.84	1.45	1.24	0.77	0.51	0.47	3.6	1.95	1.16	1.01
34	4.0	2.25	1.21	1.0	1.46	0.79	0.52	0.49	3.1	1.63	0.89	0.78
39	4.0	2.2	1.6	0.83	1.43	0.725	0.51	0.37	3.0	1.57	1.04	0.64
45	5.2	2.75	1.94	1.28	1.93	0.99	0.58	0.53	4.2	2.18	1.43	1.0
54	2.8	1.48	1.16	0.68	1.5	0.82	0.63	0.41	2.9	1.51	1.23	0.68
58	4.0	2.1	1.3	1.09	2.0	0.94	0.64	0.52	4.0	2.2	1.3	0.98
Ave.	3.61	2.16	1.44	0.9	1.32	0.89	0.59	0.37	3.3	1.98	1.32	0.83

TABLE X.—INTENSITY SERIES.

Showing the illumination measurements in foot-candles at nine representative stations for the different intensities used for the indirect system. No socket extenders used with the 40 and 25-watt lamps.

Station	Horizontal				Vertical				45°			
	800	480	320	200	800	480	320	200	800	480	320	200
Card	5.2	3.0	1.48	1.16	1.36	0.765	0.407	0.37	3.5	1.97	0.95	0.76
12	2.7	1.63	0.84	0.5	0.47	0.265	0.139	0.99	1.43	0.83	0.44	0.282
16	4.1	2.2	1.01	0.96	0.52	0.33	0.143	0.14	2.1	1.22	0.5	0.48
31	5.2	2.7	1.48	1.3	1.24	0.77	0.462	0.39	3.6	1.95	1.0	0.86
34	4.0	2.25	0.99	1.0	1.46	0.79	0.5	0.45	3.1	1.63	0.84	0.8
39	4.0	2.2	1.63	0.78	1.43	0.725	0.44	0.36	3.0	1.57	0.98	0.6
45	5.2	2.75	1.62	1.18	1.93	0.99	0.52	0.48	4.2	2.18	1.31	0.98
54	2.8	1.48	1.03	0.63	1.5	0.82	0.61	0.41	2.9	1.51	1.18	0.65
58	4.0	2.1	1.11	0.87	2.0	0.94	0.54	0.42	4.0	2.2	1.11	0.83

The results of the tests for the intensity series for the indirect system are given in Table XIII. Three hours was selected as the period of work in all of these experiments. The tests were taken only as Position I (see Fig. 1, p. 452a), the position, it will be remembered, at which six of the fixtures were in the field of view. It will be noted that there is practically no difference in the loss of efficiency of the eye for the different intensities of illumination when socket extenders were used for the shorter lamps. When socket extenders were not used for these lamps, quite a little loss of efficiency was experienced. This loss, moreover, was considerably greater for the shorter 25-watt lamps than for the 40-watt

lamps. Since the prominent variable in this case was intrins brilliancy of the ceiling spot above the reflector, the increased lo of efficiency can probably be ascribed primarily to this cause; more comprehensively stated perhaps, to the change in the magr tude of the brightness differences that were present in the field vision. For example, the ratio, lightest to darkest for the 10 watt lamps was 145; it was 133 for the 60-watt lamps; 142 f the 40-watt lamps with socket extenders; and 135 for the 2 watt lamps with socket extenders. For the 40-watt lamps wit out socket extenders, however, this ratio was raised to 326, a for the 25-watt lamps without socket extenders it was raised 374. Similar changes were also made in the other ratios: lighte to test card, lightest to reading page, etc., as may be seen by i specting Table XII.

TABLE XI.—INTENSITY SERIES.

Showing the brightness measurements in candlepower per square in for the different intensities used for the indirect system at points indica by the letters A, B, C, D, etc., see Fig. 4.

Surface measured	800 watts	480 watts	320 watts: With socket extenders	320 watts: Without socket extenders	200 watts: With socket extenders	200 watts: Withou socket e tenders
A	0.138	0.0704	0.0539	0.088	0.0352	0.0748
B	0.0715	0.0385	0.0252	0.0231	0.0165	0.0187
C	0.066	0.0352	0.0244	0.022	0.0159	0.0165
D	0.0022	0.00097	0.00079	0.00059	0.00064	0.0004
E	0.0030	0.000163	0.00119	0.0007	0.00084	0.0005
F	0.00123	0.000401	0.00035	0.00022	0.00032	0.0001
G	0.0049	0.00169	0.00145	0.00101	0.00128	0.0008
H	0.0040	0.00163	0.00129	0.00092	0.0011	0.0007
I	0.0042	0.00158	0.00127	0.0009	0.0011	0.0006
J	0.00095	0.00053	0.00038	0.00027	0.00026	0.0002
K	0.00255	0.00123	0.00088	0.00088	0.00074	0.0006
L	0.00246	0.00121	0.00085	0.00079	0.00066	0.0004
M	0.00352	0.00158	0.00106	0.00097	0.00052	0.0007
N	0.00272	0.00101	0.00076	0.00061	0.00066	0.0004
O	0.00343	0.00128	0.00076	0.00028	0.00055	0.0001
P	0.00308	0.00119	0.00067	0.00027	0.00041	0.0001
X	0.00299	0.00154	0.00109	0.0008	0.00074	0.0005
Reading page horizontal	0.0088	0.00405	0.00281	0.0022	0.00198	0.0016
Reading page 45° position	0.00431	0.00273	0.00167	0.00154	0.00117	0.0009

TABLE XII.—INTENSITY SERIES.

Showing some prominent ratios of surface brightness for the different intensities used for the indirect system. An important point of comparison for the purpose of this investigation is the ratios with and without socket extenders.[16]

Ratio	800 watts	480 watts	320 watts With socket extenders
Lightest to darkest	0.138 /0.00095 = 145.0	0.0704/0.00053 = 133.0	0.0539/0.00038 = 142.0
Lightest to test card	0.138 /0.00299 = 46.0	0.0704/0.00154 = 45.0	0.0539/0.00109 = 49.0
Lightest to reading page	0.138 /0.00431 = 32.0	0.0704/0.00273 = 26 0	0.0539/0.00167 = 32.0
2nd lightest to darkest	0.0715/0.00095 = 75.0	0.0385/0.00053 = 72.6	0.0252/0.00038 = 66.0
2nd lightest to test card	0.0715/0.00299 = 24.0	0.0385/0.00154 = 25.0	0.0252/0.00109 = 23 0
2nd lightest to reading page	0.0715/0.00431 = 16.5	0.0385/0.00273 = 14.0	0.0252/0.00167 = 15.0
3rd lightest to darkest	0.066 /0.00095 = 66.3	0.0352/0.00053 = 66.0	0.0244/0.00038 = 64.0
3rd lightest to test card	0.066 /0.00299 = 22.0	0.0352/0.00154 = 22.0	0.0244/0.00109 = 22.0
3rd lightest to reading page	0.066 /0.00431 = 15.0	0.0352/0.00273 = 12.9	0.0244/0.00167 = 14.6

Ratio	320 watts Without socket extenders	200 watts With socket extenders	200 watts Without socket extenders
Lightest to darkest	0.088 /0.00027 = 326.0	0.0352/0.00026 = 135 0	0.0748/0.0002 = 374 0
Lightest to test card	0.088 /0.0008 = 110.0	0.0352/0.00074 = 47.0	0.0748/0 00059 = 127.0
Lightest to reading page	0.088 /0.00154 = 57.0	0.0352/0.00117 = 30.0	0.0748/0.0009 = 83.0
2nd lightest to darkest	0.0231/0.00027 = 85.5	0.0165/0.00026 = 63.5	0.0187/c.0002 = 93.5
2nd lightest to test card	0.0231/0.0008 = 28.9	0.0165/0.00074 = 22.3	0.0187/0.00059 = 31.7
2nd lightest to reading page	0.0231/0.00154 = 15.0	0.0165/0.00117 = 14.0	0.0187/0.0009 = 20.8
3rd lightest to darkest	0.022 /0.00027 = 81.5	0.0159/0.00026 = 61.0	0.0165/0.0002 = 82.5
3rd lightest to test card	0.022 /0.0008 = 27.5	0.0159/0.00074 = 21.5	0.0165/0.00059 = 28.0
3rd lightest to reading page	0.022 /0.00154 = 14.2	0.0159/0.00117 = 13.6	0.0165/0.0009 = 18.3

[16] Theoretically considered, the above ratios: lightest to darkest, lightest to test card, lightest to reading page, etc., should be approximately the same for all of the wattages, if the lamps sustain the same relation to the reflector, to the ceiling, etc. A certain unevenness in these ratios will be noted, however, even when socket extenders were used with the 25 and 40-watt lamps. This is no more than is to be expected because socket extenders of only one length could be obtained, and these did not give the same relation of lamp to reflector for the 25 as for the 40-watt lamp, nor the same relation for either of these lamps as was obtained for the 60 and 100-watt lamps. Obviously too the 60-watt lamps did not sustain the same relation to the reflectors as did the 100-watt lamps.

TABLE XIII.—INTENSITY SERIES.

Showing the effect on the efficiency of the eye of varying the intensity of light in an indirect system composed of 8 units, clear tungsten lamps.

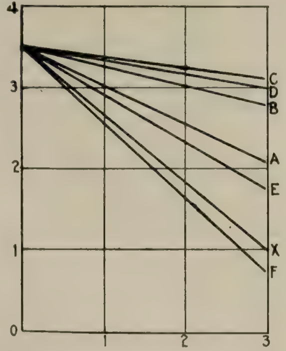
Watts		Foot-candles: Horizontal	Foot-candles: Vertical	Foot-candles: 45°	Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Total time clear ÷ total time blurred	Ratios reduced to common standard
800		5.2	1.36	3.5	9 A.M.	84.5	67.5	135	45	3.0	3.5
					12 M.	84.5	67.5	132	48	2.75	3.2
480		3.0	0.765	1.97	9 A.M.	82.5	65.0	150	30	5.0	3.5
					12 M.	82.0	65.0	148	32	4.6	3.22
320	With socket extenders ..	1.7	0.49	1.08	9 A.M.	81.0	66.0	140	40	3.5	3.5
					12 M.	81.0	66.0	137	43	3.18	3.18
320	Without socket extenders	1.48	0.407	0.95	9 A.M.	79.0	64.0	145	35	4.1	3.5
					12 M.	77.0	64.0	138	42	3.29	2.7
200	With socket extenders ..	1.33	0.39	0.87	9 A.M.	79.0	64.0	122	58	2.1	3.5
					12 M.	79.0	64.0	120	60	2.0	3.3
200	Without socket extenders	1.16	0.37	0.76	9 A.M.	78.0	62.0	149	31	4.8	3.5
					12 M.	76.0	62.0	135	45	3.0	2.1

CHART II.—INTENSITY SERIES.

Showing a comparison of the effect on the efficiency of the eye of varying the intensity of light for the four installations of lighting used: the indirect, semi-indirect, and direct systems, 8 lamps; and the direct system, 16 lamps.[17]

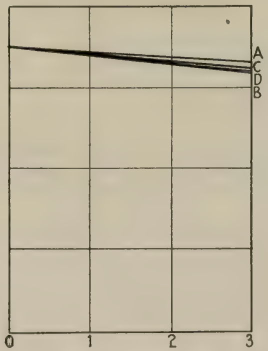
Lighting system: Semi-indirect

	Watts	Volts	Foot-candles Horizontal	Vertical	45°
A	200	107	1.6	0.45	1.15
B	200	110	1.72	0.484	1.29
C	320	107	2.2	0.58	1.52
D	320	110	2.31	0.62	1.61
E	480	107	3.3	0.94	2.4
F	800	107	6.8	1.82	4.5
X	760	107	5.8	1.45	4.0



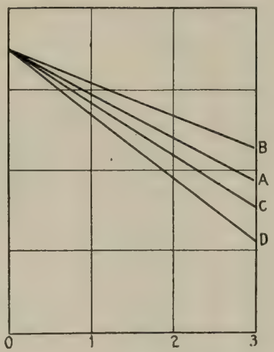
Lighting system: Indirect

	Watts	Volts	Foot-candles Horizontal	Vertical	45°
A	200	107	1.33	0.39	0.87
B	320	107	1.7	0.49	1.08
C	480	107	3.0	0.765	1.97
D	800	107	5.2	1.36	3.5



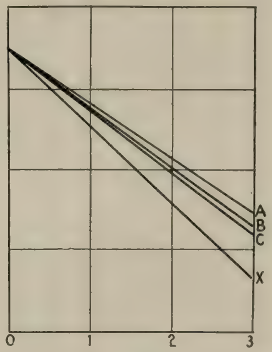
Lighting system: Direct (8 lamps)

	Watts	Volts	Foot-candles Horizontal	Vertical	45°
A	120	107	0.64	0.32	0.49
B	200	107	1.16	0.45	0.85
C	320	107	1.97	0.65	1.39
D	480	107	2.6	1.02	2.0



Lighting system: Direct (16 lamps)

	Watts	Volts	Foot-candles Horizontal	Vertical	45°
A	240	107	1.23	0.54	0.935
B	365	107	1.6	0.6	1.33
C	400	107	1.86	0.8	1.46
X	880	107	4.2	1.41	2.6

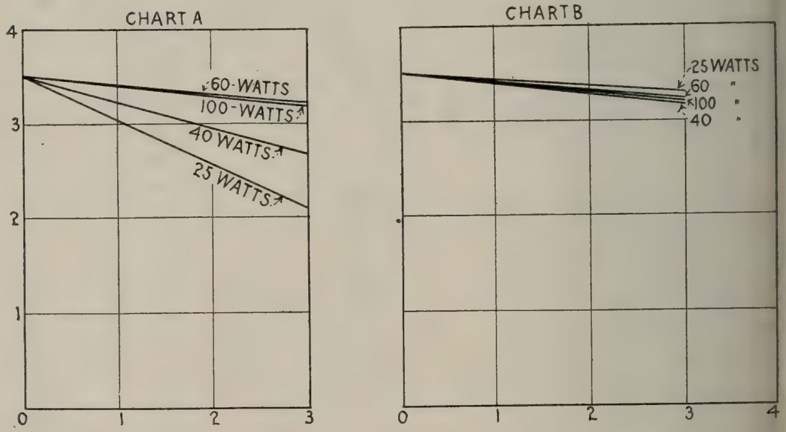


[17] For a full specification of the illumination effects, brightness and illumination measurements, brightness ratios, etc., produced by the direct and semi-indirect systems for the different wattages, see the previous paper (op. cit., pp. 428-441).

A graphic representation of the results for the indirect system with socket extenders is given in Chart II. In this chart loss of efficiency is plotted against time of work in the manner described in the preceding section. For the sake of comparison results are shown also on this chart for the direct and semi-indirect systems. A graphic representation has further been made of the results for the indirect system with and without socket extenders. This is shown in Chart III.

CHART III. -INTENSITY SERIES.

Showing the effect on loss of efficiency of changing the height of the ligh source in the reflector of the indirect lighting fixtures. The effect on surfac brightness is primarily to change the area and surface brilliancy of the spot o light thrown on the ceiling. Chart A shows the results when height o source in the reflector is changed; Chart B, the results when the height i kept approximately constant.



EYE SHADE SERIES.

This series of experiments has been conducted for the following reasons. (1) In general two methods are used to protect the eye from the source of light, eye shades and lamp shades. It is desirable to know whether the eye is protected equally well by both; and if the eye shade can be substituted for the lamp shade, what type of shade would best serve the purpose. (2) And the statement has been made to us many times that with an eye shade the three systems of artificial lighting we have used should give equally good results; and results, moreover, as good

as those given by the indirect system without an eye shade. There are in general two classes of eye shades, the translucent and opaque. Up to this time we have confined our work to the opaque shade. So far as we know it is customary to make the opaque shade with a dark lining. This kind of lining is employed probably because of some notion that it is restful to the eye to darken as much of the field of vision as is possible.[18]

The tests were begun with the opaque shade with the dark lining. What we found as the result of these tests was somewhat in contradiction to the predictions that had been made. The shade did give pretty nearly the same results for the three systems; but it did this, contrary to prediction, by improving the direct and semi-indirect systems and making worse by almost an equal amount the indirect system. That is, protected by the opaque shade, the eye lost in efficiency for the three systems by an amount somewhere near the mean of the losses experienced by it for the three systems without a shade. Nor is this result surprising when one reflects upon the conditions imposed upon the eye by an opaque shade with a dark lining. While it protects the eye from the sources of light, such a shade does not by any means eliminate harmful brightness differences in the field of vision. It in fact creates for the eye a very unnatural brightness relation, *i. e.,* it renders the whole upper half of the field of vision dark in sharp contrast with the brightly lighted lower half. The direct effect of this is a strong brightness induction (physiological) over the lower half of the field of vision which manifests itself to the observer by causing glare in surfaces that have no glare, and by increasing the glare in surfaces in which glare is already present. This, it is scarcely necessary to point out, operates against the discrimination of detail and puts the eye under strain to see its objects clearly. Moreover, the unusual and strongly irregular character of the image formed on the retina probably also sets up a warfare in the incentives given to the muscles which adjust the eye. That is, the upper half of the field of vision is dark and presents no detail. The effect of this is probably to exert a tendency to cause the muscular relax-

[18] Another popular view might be, so far as protection to the eye is concerned, to regard the opaque eye shade as the analogue of the opaque or perhaps the indirect lamp reflector and the translucent shade as the analogue of the semi-indirect reflector.

ation characteristic of the darkened field of vision. The lower half of the field is light and filled with detail. The incentive here is towards the best possible adjustment of the eye for the discrimination of detail in the objects viewed, while the rim of the shade, the sharply marked boundary between the dark and light halves of the field of vision and much nearer to the eye than the objects viewed,[19] serves as a constant and consciously annoying distraction to fixation and accommodation. These complex and somewhat contradictory impulses given to the muscles of the eye might very well, and doubtless do cause an excessive and unnatural loss of energy and efficiency in case of the prolonged adjustment of the eye needed for a period of work.

Early in the course of the tests it occurred to us that we might render the brightness distribution in the field of view presented to the eye wearing a shade more natural, and thereby improve the effect of the shade on the eye, by employing a white instead of a dark lining. By using a matt white paper[20] with a reflection coefficient of about 75 per cent. for this lining, the following effects were produced. The two halves of the field of vision were rendered much more nearly of equal brightness; the glare in the lower half of the field of vision was very noticeably lessened and the discrimination of detail was correspondingly improved; the upper half of the field of view no longer tended to give to the eye the reflexes of the darkened field of vision; and the rim of the shade did not stand out nearly so distinctly in the field of view to distract accommodation and fixation. The results of the test for loss of efficiency show, moreover, that our surmise with regard to the effect of this change on the eye was correct. The action of the white lining was greatly to improve the ability of the eye to maintain its efficiency for a period of work. As good results were not gotten, however, with the shade for any of the systems as were given by the indirect system without the shade. Since there was a still greater evenness of surface brightness in the field of view in case of the indirect system with the eye shade than without, the question arises why

[19] This rim is about three inches in front of the observer's eye when the shade is in position.

[20] Hering standard white paper was used for this lining. The reflection coefficient of the dark lining was about 6–8 per cent.

at least as good results were not obtained with the shade as without. The answer, we believe, is to be found in terms of the distraction to fixation and accommodation caused by the eye shade even when a light lining was used. For the effect of a shade on the eye even when the most favorable lining is employed is that of a constantly present distracting object with its lower margin not far removed from the center of the field of vision, and much nearer to the eye than are the objects which the observer is called upon to discriminate. It will be noticed also in Table XVII that the results were never so good for either kind of shade for the direct and semi-indirect systems as for the indirect. Since the evenness of surface brightness in the field of view was not very different for the three systems in both cases, this again probably indicates that the evenness of surface brightness is not the only one of the distribution factors that has to be taken into account in studying the effect of different conditions of lighting on the eye.

These tests were made for the same installations that were used in the distribution series. Since the use of the eye shade did not affect the illumination of the room the reader is referred for the illumination measurements to the tables of the distribution series. The distribution of surface brightness in the field of vision, however, was strongly affected. New measurements were made, therefore, of the brightness of the prominent surfaces in the field of vision. The tests were taken at Position I, see Fig. 1, p. 452a The prominent surfaces in the observer's field of vision working in this position were J, K, and L (see Fig. 4, p. 452b); the top of the table carrying test and recording apparatus, immediately in front of the observer and below the level of his eyes; the test card; the reading page in the 45 deg. position; and the white and dark lining of the eye shade as seen by the observer when the shade was in position over his eyes. The measurements of the brightness of the lining of the eye shades as seen by the observer when the shades were in position were made as follows. A surface in front of the observer was made to match in brightness the lining of the shade as it was seen by him. The brightness of this surface was then measured by the method described on page 452. In procuring the match between the comparison surface and

the lining of the shade the series of Hering matt gray papers was employed. This series consists of 50 shades ranging from a white with a reflection coefficient of 75 per cent. to black. Sheets of these differing in brightness were placed in a vertical position at a given distance in front of the observer until an approximate match was made with the lining of the shade. The gradations needed to get the final match were secured by moving the surface to and from the observer and by tilting it at different angles with the line of sight. The former adjustment carried it into parts of the room having different intensities of illumination and the latter turned it so as to receive a greater or less amount of light. In making the brightness measurements, care was taken to have the receiving surface of the photometer arm normal at its central point to the line of sight taken by the observer when the match was made. The results of these measurements are shown in Table XIV. In Table XV are given some of the prominent ratios of surface brightness in the field of vision for the shade with the dark lining; and in Table XVI, some of the prominent ratios for the shade with the white lining. In Table XVII are shown the results for the test for loss of efficiency for the shade with the dark lining; and in Table XVIII for the shade with the white lining. For purposes of comparison the results of the three systems without a shade are repeated. These are given in Table XIX. A graphic representation results of all three tables is given in Chart IV.

TABLE XIV.—Eye Shade Series.

Showing the brightness measurements in candlepower per square inch for the various surfaces in the field of vision for the direct, semi-indirect and indirect systems used when the eyes were shielded in turn by an opaque eye shade with a dark lining, and an opaque eye shade with a white lining.

Surface measured	Direct system	Semi-indirect system	Indirect system
J	0.0014	0.001	0.00095
K	0.0063	0.0046	0.00255
L	0.0042	0.0027	0.00246
Table	0.0029	0.00255	0.00233
Test card	0.00308	0.003	0.00299
Reading page 45° position	0.004	0.0039	0.00431
White lining of eye shade	0.00197	0.00204	0.00207
Dark lining of eye shade	0.000091	0.00011	0.000126

TABLE XV.—EYE SHADE SERIES.

Showing some prominent ratios of surface brightness for the direct, semi-indirect, and indirect systems used when the eyes were shielded by an opaque eye shade with a dark lining.

Ratio	Direct system	Semi-indirect system	Indirect system
Lightest to darkest	0.0063/0.000091 = 69.2	0.0046/0.00011 = 42.0	0.00431/0.000126 = 34.2
Lightest to test card.	0.0063/0.00308 = 2.04	0.0046/0.003 = 1.53	0.00431/0.00299 = 1.5
Lightest to reading page	0.0063/0.004 = 1.56	0.0046/0.0039 = 1.2	0.00431/0.00431 = 1.0
Lightest to lining of eye shade.......	0.0063/0.000091 = 69.2	0.0046/0.00011 = 42.0	0.00431/0.000126 = 34.2

TABLE XVI.—EYE SHADE SERIES.

Showing some prominent ratios of surface brightness for the direct, semi-indirect, and indirect systems used when the eyes were shielded by an opaque eye shade with a white lining.

Ratio	Direct system	Semi-indirect system	Indirect system
Lightest to darkest	0.0063/0.0014 = 3.9	0.0046/0.001 = 4.6	0.00431/0.00095 = 4.5
Lightest to test card....................	0.0063/0.00308 = 2.04	0.0046/0.003 = 1.53	0.00431/0.00299 = 1.0
Lightest to reading page................	0.0063/0.004 = 1.56	0.0046/0.0039 = 1.2	0.00431/0.00431 = 1.0
Lightest to lining of eye shade..........	0.0063/0.00197 = 3.2	0.0046/0.00204 = 2.25	0.00431/0.00207 = 2.5

TABLE XVII.—EYE SHADE SERIES.

Showing the eye's loss in efficiency as the result of 3 hours of work under the direct, semi-indirect, and indirect systems of lighting employed. (With opaque eye shade with dark lining.)

Lighting system	Watts	Foot-candles Hori-zontal	Foot-candles Verti-cal	Foot-candles 45°	Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Total time clear ÷ total time blurred	Ratios reduced to common standard
Indirect	800	5.2	1.36	3.5	9 A.M.	80.0	68	143	37	3.86	3.5
					12 M.	80.0	68	130	50	2.6	2.34
Semi-indirect	760	5.8	1.45	4.0	9 A.M.	80.0	68	126	54	2.33	3.5
					12 M.	79.5	68	110	70	1.55	2.33
Direct	880	4.2	1.41	2.6	9 A.M.	79.0	67	139	41	3.39	3.5
					12 M.	79.0	67	124	56	2.21	2.27

TABLE XVIII.—EYE SHADE SERIES.

Showing the eye's loss in efficiency as the result of 3 hours of work under the direct, semi-indirect, and indirect systems of lighting employed. (With opaque eye shade with white lining.)

Lighting system	Watts	Foot-candles Hori-zontal	Foot-candles Verti-cal	Foot-candles 45°	Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Total time clear ÷ total time blurred	Ratios reduced to common standard
Indirect	800	5.2	1.36	3.5	9 A.M.	85.0	68	118	62	1.9	3.5
					12 M.	85.0	68	115	65	1.77	3.18
Semi-indirect	760	5.8	1.45	4.0	9 A.M.	85.0	68	128	52	2.46	3.5
					12 M.	85.0	68	124	56	2.21	3.13
Direct	880	4.2	1.41	2.6	9 A.M.	85.0	70	105	75	1.4	3.5
					12 M.	84.5	70	100	80	1.25	3.07

TABLE XIX.—EYE-SHADE SERIES.

Showing the eye's loss in efficiency as the result of 3 hours of work under the direct, semi-indirect, and indirect systems of lighting employed (No eye shade.)

Lighting system	Watts	Foot-candles Hori-zontal	Verti-cal	45°	Time	Maximal distance at which test object can be seen clear
Indirect	800	5.2	1.36	3.5	9 A.M.	84.5
					12 M.	84.5
Semi-indirect	760	5.8	1.45	4.0	9 A.M.	80.5
					12 M.	79.5
Direct	880	4.2	1.41	2.6	9 A.M.	81.0
					12 M.	78.0

	Work-ing dis-tance	Total time clear	Total time blurred	Total time clear ÷ total time blurred	Ratios reduced to common standard
Indirect	67.5	135	45	3.00	3.5
	67.5	132	48	2.75	3.2
Semi-indirect	68.5	142	38	3.73	3.5
	68.5	92	88	1.64	0.97
Direct	68.0	139	41	3.39	3.5
	68.0	771	109	0.69	0.671

As yet we have not determined the effect of translucent shades on the eye. In attempting to deal in a general way with this class of shades we have the same type of difficulty to face that we have in case of the semi-indirect reflector. That is, we may have shades varying from transparent to opaque, and sharing in the merits and demerits of each extreme. Our judgment would be, however, that it would be very difficult to get a translucent shade that would give as good results as an opaque shade with a light lining; for the translucent shade when made sufficiently opaque to give the needed reduction to the image of the source will darken too much the upper half of the field of vision and thereby simulate too much the condition given by the opaque shade with the dark lining to give the best results for comfortable and efficient seeing. Moreover, from the results that have already been obtained with the opaque shade and from the principles it seems fair to infer from these results, it seems very probable to us that as good effects for seeing should not be expected from the use of

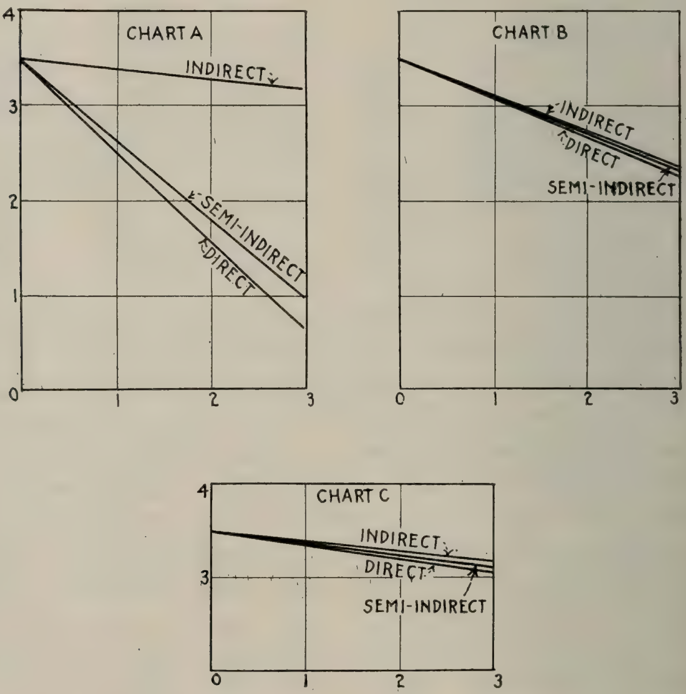
any kind of eye shade as may be gotten from lamp-shades. That is, if we are to secure the best results for seeing, the shade should be put on the lamp, not on the eye.

THE ANGLE AT WHICH THE LIGHT FALLS ON THE WORK.

The object of these experiments was to find out whether the

CHART IV.—EYE SHADE SERIES.

Showing the effect on loss of efficiency of opaque eye shades with dark and with white lining for the installations direct, semi-indirect, and indirect with the same intensity of light at the point of work. Chart A shows results without shade; Chart B, with shade having dark lining; Chart C· with shade having white lining.



difference in the angle at which the light falls on the work produces an effect on the eye that can be detected by the test we have used for loss of efficiency. For the purpose of this preliminary investigation it was decided to make the general illumination of the room such as to cause the eye little loss of effi-

ciency as the result of the period of work; and to add to that at the point of work a component of light which was less diffuse in order that the amount of light entering the eye would be more dependent upon the angle at which the reading page was held.

The general illumination was obtained from the indirect system used in the work of the preceding sections with lamps totalling 800 watts. The less diffuse component at the point of work was obtained from a 60-watt lamp with a porcelain reflector of the desk lamp type. This lamp was turned into the horizontal position and was placed behind the observer and to the left so that the light came over the left shoulder. When in the position for which the test was taken the tip of the lamp was slightly above the level of the observer's eye, at a distance of 1 meter from the left eye.

The illumination and brightness measurements for the test room illuminated by the indirect system, 800 watts, are given on pp. 469 and 471. These measurements were not greatly changed by the addition of the 60-watt lamp behind the observer. Because of the presence of this lamp, however, the following measurements were added to those given on pp. 469 and 471: the horizontal, vertical, and 45 deg. components of light at the point of work; the brightness of the test card in place for the test; and the brightness of the reading page when held respectively in the positions which gave the least and the greatest amounts of specular reflection. The illumination measurements at the point of work are given in Table XX. The brightness of the test card was 0.00365 cp. per sq. in.; of the reading page in the position that gave the least amount of specular reflection, 0.0059 cp. per sq. in.; and in the position that gave the greatest amount of specular reflection, 0.0077 cp. per sq. in. A mirror surface was used as an aid in locating the position of least and greatest specular reflection. The results of the test for three hours of work done with the reading page in these two positions are also given in Table XX. A graphic representation of the results of this table is shown in Chart V.

THE EFFECT OF DIFFERENT CONDITIONS OF LIGHTING ON THE FIXATION MUSCLES OF THE EYE.

The test we have employed thus far in the conduct of our

work is one designed to show the effect of different conditions of lighting on the ability of the eye to hold its efficiency for clear seeing for a period of three minutes. In itself this test is not

TABLE XX.—THE ANGLE AT WHICH THE LIGHT FALLS ON THE WORK.

Showing the effect on loss of efficiency of the angle at which the light falls on the work.

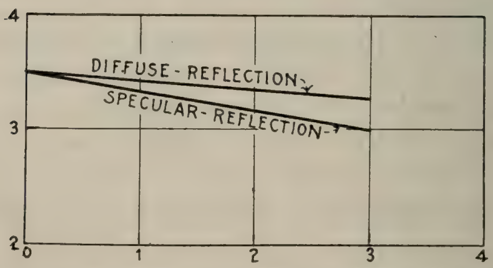
Kind of reflection from reading page during work period	Foot-candles at test-card: Horizontal	Vertical	45°	Time	Maximal distance at which test object can be seen clear
Diffuse	5.3	1.84	3.9	9 A.M.	89
				12 M.	89
Specular	5.3	1.84	3.9	9 A.M.	89
				12 M.	89

	Working distance	Total time clear	Total time blurred	Total time clear ÷ total time blurred	Ratios reduced to common standard
Diffuse	73	139	41	3.39	3.5
	73	137	43	3.18	3.27
Specular	73	137	43	3.18	3.5
	73	132	48	2.73	3.0

analytical in principle. The results, as is stated above, are expressed in terms of an aggregate loss of function. The contributive factors may be inferred from the nature of the test, but

CHART V.—THE ANGLE AT WHICH THE LIGHT FALLS ON THE WORK.

Showing the effect on loss of efficiency of the angle at which the light falls on the work.



the test is not in itself designed to separate them out. And indeed it is a question whether any practical good can accrue to the practise of lighting from a knowledge of just what part of

the visual apparatus it is that falls off in function as the result of an unfavorable condition of lighting. Obviously the chief need is to find out what are the conditions that cause the eye to lose its ability to see clearly and to avoid these conditions in planning and installing a lighting system. From the beginning we have had in mind, however, an analysis of effect. Our tests for the sensitivity of the retina showed, for example, that very little, if any, of the difference in results we have gotten for the four types of lighting we have employed can be ascribed to a loss in the efficiency of the retina, or the light sensitive part of the visual apparatus. Three sets of factors are involved in clear seeing: (1) the sensitivity of the eye to colored and white light; (2) the ability to make fine space discriminations which is in part dependent upon our third factor; and (3) accurate fixation and accommodation. Both fixation and accommodation are the result of muscular action. When the muscles lose in tone because of excessive use or by sharing in a general condition or state of the body, the eye loses correspondingly in its power to sustain clear seeing. If, for example, the muscles of accommodation have fallen off in efficiency the lens is no longer held in the adjustment needed to bring the light to a sharp focus on the retina and loss of detail and blurring result; or, if it be the fixation muscles that have suffered the loss, the eyes cannot be continuously held in such a position that the images of the object viewed fall symmetrically on the fovea of each. When this latter condition is present loss of detail results from two causes. (1) The fovea and region immediately surrounding it are the most highly developed parts of the retina and the best fitted for the light and space discriminations needed for clear seeing. Moreover, the refracting media of the eye give the clearest images when the axis of the cone of rays from the object viewed deviates as little as possible, consistent with the mechanism of the eye, from the optic axis. And (2) if the images in the two eyes do not fall more or less symmetrically upon the fovea of each they are not accurately combined into one, and blurring and loss of detail results from the doubling of the objects seen. It is our purpose as fast as possible to isolate the effect of the three systems of lighting we have used on each of the above named factors. In

the work of the present section the effect of these systems on the fixation muscles has been studied.

The doubling of the image seen when the fixation muscles lose their power of co-ordinated action furnishes us with our clue for a test for the loss of efficiency of these muscles. That is, just as blurring and the loss of ability to discriminate detail is taken as the criterion of the loss of acuity of vision, so will the doubling of the image seen be taken as our index of the loss of the co-ordinated action of the fixation muscles. If one were to stare continuously for an interval of time with natural vision at a simple test object, as, for example, a vertical line, doubling might be detected especially if there had been protracted strain or considerable loss of power to co-ordinate. For the purpose of our work, however, greater sensitivity than this would be needed. Obviously sensitivity can be added by putting the eyes under strain to combine their images. When this is done, even when the muscles are fresh, if the object is looked at or fixated for an interval of time it will be seen alternately as one and as two. The proportion or ratio of the time seen as one to the time seen as two can be regulated by the amount of initial strain under which the eyes are put to combine their images. The regulation of this ratio is empirical and of importance; for as is the case with the test for loss of efficiency for clear seeing, the sensitivity of the test depends to a considerable extent upon the initial value that is given to this ratio. The eyes may be put under strain to combine their images by interposing between them and the object viewed weak prisms and so adjusting them and regulating the distance of the object from the eye that with the maximum of effort to see it as one it is seen alternately as one and as two in the proportion desired.[21] This result can be accom-

[21] It would seem that the above principle might be utilized to advantage by the opthalmologist in testing the extrinsic muscles of the eye. The abduction and adduction tests, for example, determine only what the muscles are able to do by momentary effort. Obviously, however, it is not what the muscles are able to do by a momentary effort or jerk that measures their ability to hold the eyes continuously adjusted for work. It is rather their endurance or what they are able to accomplish in an interval of time. An expression may be had for this either for the eyes conjointly or separately by the method described above. That is, the prisms may be put in front of either one or both eyes and the ratio be determined of the time the object is seen as one or as two for whatever interval of time the operator may select. Similarly, it seems to the writers that the time element might be introduced to ad-

(*Continued on next page.*)

plished still more conveniently, however, by using an adaptation of the Brewster stereoscope. In this case a stereograph consisting of two vertical lines exactly alike may be used as the test object. In the stereograph employed in our test the vertical lines were 2.5 cm. long and were printed on the card 4.5 cm. apart or at 2.25 cm. from the center of the card. When this was put in a sliding carrier and was made to approach the eyes, a position was reached at which with the maximum of effort the observer was no longer able to see the two vertical lines as one. They were seen alternately as one and as two. In making the test the hood was removed from the stereoscope so that the eyes were fully exposed to the conditions of illumination that were being tested. The stereoscope was mounted in front of the eyes of the observer in position at the point of work. The distance of the carrier containing the test object from the observer's eyes was adjusted until the proper ratio of time seen as one and time seen as two was obtained. Having determined this position a record was made of the time seen as one and the time seen as two for three minutes at the beginning and the close of work. The ratio of the sum of these intervals may in either case be taken as a measure at that time of the power of the fixation muscles to act in co-ordination for three minutes of continuous effort; and the decrease in this ratio from the beginning to the close of work may be taken as a measure of the loss in that power, sustained as the result of work. In making this test the same recording apparatus was used as was employed in the test for loss of efficiency for clear seeing. That is, the record was traced on a kymograph by means of an electro-magnetic marker and a

vantage into the visual acuity test used by the ophthalmologist when the cycloplegic is not employed or in cases of post-cycloplegic refraction. Is it, for example, enough to know that the eye has 20/20 acuity or can discriminate a certain standard visual angle by momentary effort? Would it not give a more complete repreentation of the functional condition of the eye to know what it can discriminate clearly through an interval of time; or better still perhaps, for what proportion of an interval of time it can discriminate a certain detail or standard visual angle clearly? For example, just as a fatigued eye may for the moment under the spur of the test overcome the functional results of fatigue, so might small errors of refraction be overcome for the moment by muscular effort, especially in the cases in which the muscles of the eye are unusually strong. But just as the fatigued muscle can not do this through an interval of time, so it would seem that a residual error of refraction might not be so easily masked through an interval of time by means of muscular effort. In short, this form of test is suggested as affording possibly a closer approximation to the conditions and demands imposed upon the eye during a period of work than is afforded by the acuity test based upon the momentary judgment.

telegraph key, and a time line was run beneath the record by means of a Jacquet chronograph registering seconds.

The test for the effect on the fixation muscles of a period of work was made under the same installations, conditions of work, and with the same observers that were used in the distribution series. The test, however, was made at only one of the positions used in that series, namely, the position at which the greatest loss of efficiency was obtained. (See Position I, Fig. 1, p. 452a.) At this point, it will be remembered, six of the lighting

TABLE XXI.—FIXATION MUSCLES SERIES.

Showing the loss of efficiency of the fixation muscles as the result of 3 hours of work under the direct, semi-indirect, and indirect systems of lighting employed.

Lighting system	Watts	Foot-candles: Horizontal	Foot-candles: Vertical	Foot-candles: 45°	Time	Distance at which test object is normally seen single
Indirect	800	4.2	0.99	2.5	9 A.M.	18
					12 M.	18
Semi-indirect	760	4.8	0.98	2.6	9 A.M.	18
					12 M.	18
Direct............	880	3.9	1.0	1.99	9 A.M.	18
					12 M.	18

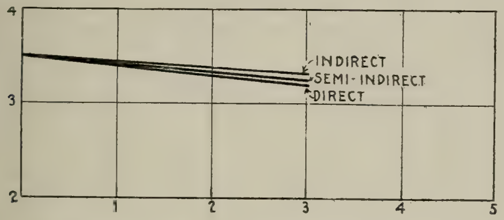
Lighting system	Working distance	Total time single	Total time double	Total time single ÷ total time double	Ratios reduced to common standard
Indirect	22	142	38	3.7	3.5
	22	140	40	3.5	3.31
Semi-indirect	22	141	39	3.6	3.5
	22	138	42	3.28	3.24
Direct	20	153	27	5.66	3.5
	20	151	29	5.21	3.21

units were in the field of view. The specification of the lighting effects produced by these installations are given on pp. 452a-459 Nothing need be added at this point to these specifications but the brightness of the stereograph or the test object in position for the three systems of lighting, and the illumination measurements at the test card. The brightness measurements are as follows. The brightness of the card, corrected for the absorption of the prisms of the stereoscope was for the direct system 0.00172 cp. per sq. in.; for the semi-indirect system,

0.00163 cp. per sq. in.; and for the indirect system, 0.00167 cp. per sq. in. New illumination measurements were needed at the test card because the card had to be moved closer to the eyes than was the case in the tests for loss of efficiency for clear seeing, which brought it into a region of different illumination. These measurements are given in Table XXI. The results of our tests for loss of efficiency of the fixation muscles for the three systems of lighting are given also in this table. These results show (a) that very little loss of co-ordination is suffered by the fixation muscles as the result of three hours of work under the systems selected; and (b) that there is very little difference in

CHART VI.—FIXATION MUSCLE SERIES.
Showing the loss of efficiency of the fixation muscles as the result of 3 hours of work under the direct, semi-indirect, and indirect systems of lighting employed.

		Foot-candles		
Lighting system	Watts	Horizontal	Vertical	45°
Indirect	800	4.2	0.99	2.5
Semi-indirect ..	760	4.8	0.98	2.6
Direct.........	880	3.9	1.0	1.99



the effect for the three systems. Since there is no reason for thinking that the test has not as great sensitivity as the test for loss of efficiency for clear seeing, and since the same observers, conditions of lighting and working were used as in the former tests, it does not seem to us at this time that the loss of efficiency for clear seeing that is sustained under these conditions, shown by the former tests, can be ascribed to any great extent to an effect on the muscles of fixation. In a later report experiments will be described in which the effect on the muscles of accommodation has been studied.

A graphic representation of the results of Table XXI is shown in Chart VI.

THE EFFECT OF MOTION PICTURES ON THE EFFICIENCY OF THE EYE.

The belief that motion pictures subject the eyes to undue strain is too prevalent to need more than mention in passing. All are familiar with the conditions,—the initially dark-adapted and highly sensitized eye, the comparatively brilliant screen with its dark surrounding field, the flickering light, and the shifting and very often unsteady pictures. We have already seen that differences in surface brightness of considerable magnitude in the field of vision cause loss of efficiency and produce discomfort, and we have discussed the causes for these effects. We have nothing further to add to that discussion here. We are, however, facing for the first time in our work the question of the effect upon the eye of a flickering light and lack of steadiness in the object viewed. The following reason is suggested why a flickering or unsteady picture may cause loss of efficiency. The eye is so constituted that when its images lose in clearness or distinctness it is incited to a muscular readjustment to bring about the clearness needed. Ordinarily in seeing, the conditions for loss in clearness come about primarily through the difference in the distance or direction from the eye of the objects which are successively viewed. In motion pictures, however, the changing clearness of the objects viewed is not due to any change in their distance or direction from the eye; nor to anything in fact which the readjustment of the eye can remedy to any considerable degree. The effort expended, therefore, is of little avail for seeing, if, indeed, the new setting of the parts is not a detriment to clear seeing and a condition which in turn must be corrected. This should, and doubtless does, lead to muscular strain and loss of efficiency. It was decided, therefore, to make an explorative investigation to determine whether there is an effect of motion pictures on the eye which can be detected by our test for loss of efficiency. The tests were conducted in a local theater, selected primarily because of the favorable conditions that prevailed. The definition at the screen was good and the pictures were unusually steady and free from flicker. The conditions were, we think, fairly representative of what is found in the better class of motion picture houses.

The tests were taken immediately before and after two hours of observation of the pictures. During the exhibition the observer sat directly in front of the center of the screen. The observation was made at successive times at three distances from the screen,—in the front, middle, and the back of the house. These positions were respectively 25, 48, and 71 ft. (7.62, 14.6, and 21.6 m.) from the screen. The room in which the pictures were shown was 78 ft. (23.7 m.) long and 48 ft. (14.6 m.) wide. The tests were taken in a room 14 ft. (4.2 m.) long, 9 ft. (2.74 m.) wide, 11 ft. (3.35 m.) high, adjoining the stage. The walls and ceiling of this room were of rough plaster, painted a flat white. When taking the test the observer sat facing one of the side walls of the room, 1.5 m. distant. The room was lighted for the purpose of the test by one 100-watt and one 60-watt clear tungsten lamp suspended behind and slightly to the right of the observer when in position for the test, at about 2 ft. (0.6 m.) above the level of his eyes. The source of light was thus entirely out of the field of view and the light fell evenly and without shadow on the test card and the wall in front of the observer. At the point of the test card, the illumination measured with the receiving test plate of the photometer in the horizontal plane was 1.3 foot-candles; in the vertical plane, 1.9 foot-candles; and in the 45 deg. plane, 2.3 foot-candles. The surface brightness of the test card was 0.003256 cp. per sq. in., and that of the wall directly behind the card was 0.002288 cp. per sq. in. The distribution of surface brightness on the wall which the observer faced was very even. At the point of maximum brightness to the right of the observer, as nearly as that point could be located, the brilliancy was 0.00308 cp. per sq. in.; and to the left of the observer, 0.002024 cp. per sq. in.

In order that there might be no intermission between the pictures for changing the films, two projection machines were used. The following is the specification of the apparatus employed as given by the operator.

Type of machine, Powers 6—A Projector.

Lens equipment, 1 pair pearl white condensers, 6½ in. F. L.

1 Bausch and Lomb objective combination, 4¾ in. E. F.

Lamp, 1 10,000-cp. adjustable arc.
Carbons, 5/8 in. cored bio's.
Current, 22 volt a. c. through Halberg transformer.
Line current, 28–30 amperes.
Arc voltage, 45–50 volts.
Length of throw or distance from objective to screen, 72 ft. (21.9 m.)
Screen, sheet muslin sized and coated with flat white alabastine.
Speed of film through machine, 66 ft. 8 in. (20.3 m.) per min.
Number of pictures per 1 ft. (0.3 m.) of film, 16.
Size of picture on film, 3/4 in. (1.9 cm.) high by 15/16 in. (2.38 cm.) wide.
Size of picture on screen, 11 ft. (3.35 m.) high by 14 ft. (4.26 m.) wide.
Approximate brightness of screen with film removed from projector, 3.47 cp. per sq. in.

Exceptional steadiness, it may be said, is given to the movement of the film and, therefore, to the picture in this type of projector by the special type of intermittent movement that is employed. Details of this movement need not be given here. As has already been stated, our reason for making the test in this particular theater was the comparative steadiness of the pictures and the comparative freedom from flicker, that was obtained.

The results of the tests are shown in Table XXII. Quite a great deal of loss of efficiency is shown as the result of two hours of observation. The nearer the observer was to the screen, the greater was this loss found to be. The loss, however, so far as we can tell, is no greater than is caused by steady work under the direct and semi-indirect installations of lighting used in our distribution series. Unfortunately, we have not for the purposes of comparison, results for the same observer for the same length of time of exposure for the two sets of condition. The loss for observer R for two hours observation of the motion pictures was not nearly so great as for three hours of reading from good print and paper, under the direct and semi-indirect systems of lighting. But comparing the results for observer G for two hours of reading from the same type and paper with those for observer R for two hours observation of the pictures the

loss seems to be about the same. That is, our results indicate that while the eyes are strained a great deal by the observation

TABLE XXII.—MOTION PICTURE SERIES.

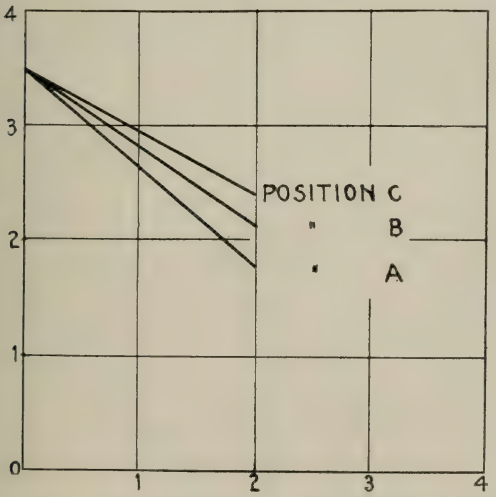
Showing the loss of efficiency of the eye caused by two hours' observation of motion pictures.

Position	Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Total time clear ÷ total time blurred	Ratios reduced to common standard
25 ft. (7.62 m.) from projection screen..	8 P.M.	86.2	70.5	123	57	2.14	3.5
	10 P.M.	86.1	70.5	95	85	1.12	1.79
48 ft. (14.63 m.) from projection screen..	8 P.M.	85.8	71.0	128	52	2.46	3.5
	10 P.M.	85.6	71.0	108	72	1.5	2.13
71 ft. (21.64 m.) from projection screen..	8 P.M.	86.0	69.0	137	43	3.19	3.5
	10 P.M.	86.0	69.0	124	56	2.2	2.42

CHART VII. MOTION PICTURE SERIES.

Showing the loss of efficiency of the eye caused by two hours observation of motion pictures.

Position A .... 25 ft. from projection screen
Position B .... 48 ft. from projection screen
Position C .... 71 ft. from projection screen



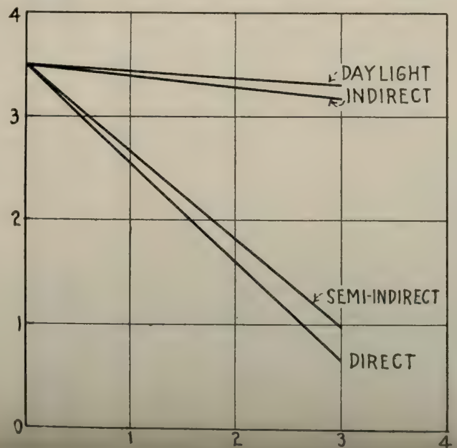
of moving pictures, even in the better moving picture houses, they are damaged little more by that in all probability than they are by

CHART VIII.

Distribution Series (Observer R)

Showing the loss of efficiency of the eye as the result of three hours of reading under the systems of direct, semi-indirect, and indirect lighting used, and daylight.

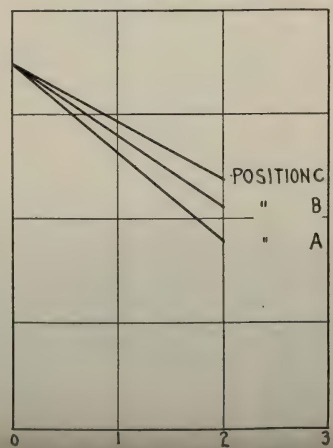
Lighting system	Watts	Foot-candles Horizontal	Vertical	45°
Daylight	—	5.5	1.32	4.2
Indirect	800	5.2	1.36	3.5
Semi-indirect .	760	5.8	1.45	4.0
Direct	880	4.2	1.41	2.6



Motion Picture Series (Observer R)

Showing the loss of efficiency of the eye caused by two hours observation of motion pictures.

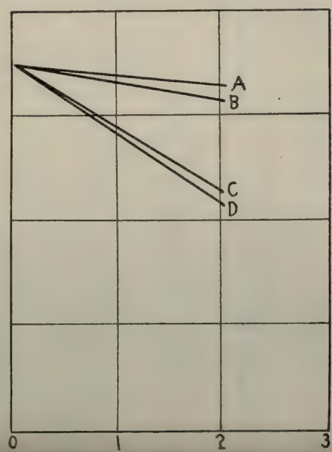
Position A, 25 ft. from projection screen
Position B, 48 ft. from projection screen
Position C, 71 ft. from projection screen



Distribution Series (Observer G)

Showing the loss of efficiency of the eye as the result of two hours reading under the systems of direct, semi-indirect, and indirect lighting used, and daylight.

	Lighting system	Watts	Volts	Foot-candles Hor.	Ver.	45°
A	Daylight	—	—	5.5	1.32	4.2
B	Indirect	800	107	5.2	1.36	3.5
C	Semi-indir't	760	107	5.8	1.45	4.0
D	Direct	880	107	4.2	1.41	2.6



reading steadily the same length of time under the greater part of the lighting that is now in actual use.

A graphic representation of the results of Table XXII is given in Chart VII. For the sake of comparing the effect of motion pictures on the eyes with the effect of reading steadily under the direct, semi-indirect, and indirect systems of lighting we have employed, Chart VIII has been prepared.

THE TENDENCY OF DIFFERENT LIGHTING CONDITIONS TO PRODUCE DISCOMFORT, AND A COMPARISON OF THE TENDENCY OF THESE CONDITIONS TO CAUSE LOSS OF EFFICIENCY AND TO PRODUCE DISCOMFORT.

In the former papers we have held that the general level or scale of efficiency of the fresh eye, loss of efficiency as the result of work, and the tendency to produce discomfort are all separate aspects of the problem of lighting in its relation to the eye, and that our knowledge of each must be obtained by different methods of investigation. A correlation between these three moments is doubtless possible, but that correlation should be founded upon the results of careful investigation; it should not be assumed. It is our purpose in this section of the paper to show the relative tendency of the different conditions of lighting we have used to produce discomfort, and to make a rough comparison of each condition to cause loss of efficiency and to produce discomfort. Any comparative study of the conditions producing discomfort necessitates a means of estimating discomfort. It is obvious that the core of the experience of discomfort is either a sensation or a complex of sensations. As such it should have a limen or threshold just as other sensations have; and just as we are able in general to estimate sensitivity in terms of the threshold value so should we in this case be able to use the threshold value in estimating the eye's sensitivity or liability to discomfort under a given lighting condition. Threshold values are usually determined by finding how much energy or intensity of a given stimulus, applied for a short interval of time, is required to arouse a just noticeable sensation. This form of procedure, however, is not adapted to the needs of our problem. It is much better to reverse the process and find how long the eye has to be exposed to a stimulus of a given intensity to arouse just noticeable discomfort. Our threshold thus

becomes a time threshold and is measured in units of time instead of units of intensity. In order to determine whether the judgment of the threshold of discomfort can be made with certainty and to perfect the method and to test in general its feasibility, an abstract investigation was undertaken first, running through an entire year, in which a better and more convenient control of conditions could be secured than is possible in the investigation of a concrete lighting situation. That is, we undertook to determine the comparative sensitivity of the eye to discomfort when a single source of light was exposed in different parts of the field of vision. In order to carry out this investigation a lamp house with a circular opening in one side 3 cm. in diameter was attached to the arm of a perimeter in such a way that the opening was always directed towards the observer's eye. In the lamp house could be placed a lamp of whatever candlepower was desired. The arm of the perimeter could be shifted to any meridian in which it was desired to work and the lamp house could be moved at will along this arm. It was thus possible to expose the light for any length of time in any part of the field of vision that was desired. Working in this way we have not only investigated the effect of many types of variation of the position of the light in the field of view, the effect of intensity of light, etc.; but we have studied and standardized the factors that influence the sensitivity and reproducibility of the judgment and have given our observers the training that was needed for the concrete investigation. In making the concrete investigation we have used every variation of the conditions of lighting described in this and the preceding paper. That is, the tendency to produce discomfort, measured in terms of the value of the time threshold, has been determined for all the conditions of lighting we have used in the tests for loss of efficiency. Two cases may be made of the investigation,—a determination of the tendency to cause discomfort when the eye is at rest, and a determination of this tendency when the eye is at work. Both of these cases were included in our investigation. The following determinations were made. (a) The time threshold of discomfort was gotten when the observer was sitting with the accommodation muscles relaxed and with the fixation muscles as nearly relaxed as was practica-

TABLE XXIII.—DISTRIBUTION SERIES.

Showing a comparison of the tendency of the direct, semi-indirect, and indirect installations of lighting used in the distribution series to cause loss of efficiency and to produce discomfort. The loss of efficiency is the result of three hours of work. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

Position of observer	Lighting system	Watts	Foot-candles			Per cent. loss of efficiency	Time limen of discomfort in seconds (not reading)	Time limen of discomfort in seconds (reading)
			Horizontal	Vertical	45°			
I.	Indirect	800	5.2	1.36	3.5	8.6	263	100
	Semi-indirect	760	5.8	1.45	4.0	72.0	15	8
	Direct	880	4.2	1.41	2.6	81.0	10	9
II.	Indirect	800	5.1	1.98	4.2	6.3	259	103
	Semi-indirect	760	6.1	2.5	4.7	37.0	26	14
	Direct	880	4.65	2.75	4.4	58.3	20	13
III.	Indirect	800	3.9	2.1	4.0	7.7	255	99
	Semi-indirect	760	5.0	2.6	5.4	22.0	120	35
	Direct	880	4.0	2.9	4.6	31.0	55	24
IV.	Indirect	800	2.9	2.1	3.6	6.6	265	101
	Semi-indirect	760	3.4	3.0	4.4	19.0	240	87
	Direct	880	3.0	3.4	4.5	23.0	235	57

TABLE XXIV.—INTENSITY SERIES.

Showing a comparison of the tendency of the direct, semi-indirect and indirect installations of lighting for the different intensities used in the intensity series to cause loss of efficiency and to produce discomfort. The loss of efficiency is the result of three hours of work. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

Lighting system	Watts	Foot-candles			Per cent. loss in efficiency	Time limen of discomfort in seconds (not reading)	Time limen of discomfort in seconds (reading)
		Horizontal	Vertical	45°			
Indirect..........	800	5.2	1.36	3.5	8.6	263.0	100
	480	3.0	0.765	1.97	8.0	265.0	103
	320 (with socket extenders)	1.7	0.49	1.08	9.1	256.0	98
	200 (with socket extenders)	1.48	0.407	0.95	5.7	251.0	104
	320 (without socket extenders)	1.33	0.39	0.87	23.0	50.0	33
	200 (without socket extenders)	1.16	0.37	0.76	40.0	20.0	14
Semi-indirect.....	320	2.2	0.58	1.52	11.4	102.0	35
	200	1.6	0.45	1.15	40.9	62.0	16
	480	3.3	0.94	2.4	50.0	50.0	15
	760	5.8	1.45	4.0	72.0	15.0	8
	800	6.8	1.82	4.5	78.0	14.0	3
Direct (16 lamps).	240	1.23	0.54	0.935	57.4	23.5	17
	365	1.6	0.6	1.33	62.0	14.0	11
	400	1.86	0.8	1.46	65.0	12.0	11
	880	4.2	1.41	2.6	81.0	10.0	9
Direct (8 lamps)..	200	1.16	0.45	0.85	34.3	56.0	27
	120	0.64	0.32	0.49	45.5	52.0	15
	320	1.97	0.65	1.39	55.5	23.0	13
	480	2.6	1.02	2.00	67.0	20.0	12

ble under the conditions. That is, the observer sat in the positions shown in Fig. 1, p. 452a, and took an easy fixation of an area at the level of the eye on the opposite wall of the room. The fixation distance, for example, for Position I, Fig. 1, p. 452a, was 22 ft. Since blinking was found to be one of the variable factors which influ-

TABLE XXV.—EYE SHADE SERIES.

Showing a comparison of the tendency of the direct, semi-indirect, and indirect installations of lighting used in the distribution series to cause loss of efficiency and to produce discomfort when the eye was protected by an opaque eye shade with a dark lining and by an opaque eye shade with a white lining. The loss of efficiency is the result of three hours of work. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

Lining of eye shade	Lighting system	Watts	Foot-candles Horizontal	Vertical	45°	Per cent. loss of efficiency	Time limen of discomfort in seconds (not reading)	Time limen of discomfort in seconds (reading)
White	Indirect	800	5.2	1.36	3.5	9.1	85	50
	Semi-indirect .	760	5.8	1.45	4.0	10.6	81	48
	Direct	880	4.2	1 41	2.6	12.0	75	45
Dark	Indirect	800	5.2	1.36	3.5	33.0	23	19
	Semi-indirect .	760	5.8	1.45	4.0	33.4	19	15
	Direct	880	4.2	1.41	2.6	35.0	16	13

TABLE XXVI.—THE ANGLE AT WHICH THE LIGHT FALLS ON THE WORK.

Showing a comparison of the tendency to cause loss of efficiency and to produce discomfort of the angle at which the light falls on the work. The loss of efficiency is the result of three hours of work. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

Kind of reflection from reading page	Foot-candles Horizontal	Vertical	45°	Per cent. loss of efficiency	Time limen of discomfort in seconds (reading)
Diffuse	5.3	1.84	3.9	6.6	95
Specular....	5.3	1.84	3.9	14.3	30

ence the tendency to produce discomfort, the amount of blinking was made constant from test to test. This was accomplished by having the observer blink at equal intervals during the test, timing himself by means of the stroke of a metronome. The interval most natural and suitable for this purpose was determined for

each observer separately. In the results given in the follo- ing table a three-second interval was used. And (b) the ti threshold of discomfort was determined when the observer w reading from print and paper similar to that used in the lc of efficiency tests. In these tests all the conditions were kept nearly the same as they were in the work on loss of efficiency was possible. The results of both of these sets of experime on the tendency to produce discomfort are shown in Tab XXIII–XXVI. The tendency to produce discomfort should estimated, roughly speaking, probably as inversely proportio to the time it was required for discomfort to be set up. The ti required for discomfort to be set up is given in the tables. order to make convenient a comparison of the tendency of various conditions of lighting to cause loss of efficiency and produce discomfort the percentage loss of efficiency caused the given lighting conditions is given in a parallel column in e table. The percentage loss of efficiency was computed by divi- ing the loss in the ratio of time seen clear to time seen blur sustained as a result of work by 3.5, the standard ratio to wh all the ratios at the beginning of work were reduced. A ro correspondence of the tendency to produce discomfort and cause loss of efficiency will be noted in every case. This c- respondence by no means amounts to a 1 : 1 correlation, howe In Table XXIII is given the comparison of the tendency to ca loss of efficiency and to produce discomfort for the distribut series; in Table XXIV, for the intensity series; in Table X for the eye shade series; and in Table XXVI, for the se showing the effect of the angle at which the light falls on work.

In conclusion we wish to state that in this work, and the w reported in the former papers, the purpose has been prima to procure methods of working and to find out, as broadly one may, the applicability of these methods to the problems s rounding the hygiene of the eye. While in many places atten has been called to results that seemed to have general significa the intention has been, in general, to limit all comments conclusions strictly to the conditions under which the work done.

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A RÉSUMÉ OF EXPERIMENTS ON THE PROBLEM OF LIGHTING IN ITS RELATION TO THE EYE

THE work of which this paper is a brief outline was done under the auspices of the American Medical Association. The object of the work has been to compare the effect of different lighting conditions on the eye and to find the factors in a lighting situation which cause the eye to lose in efficiency and to experience discomfort.

Confronting the problem of the effect of different lighting conditions on the eye, it is obvious that the first step towards systematic work is to obtain some means of estimating effect. The prominent effects of bad lighting systems are loss of efficiency, temporary and progressive, and eye discomfort. Three classes of effect, however, may be investigated: (1) the effect on the general level or scale of efficiency for the fresh eye; (2) loss of efficiency as the result of a period of work; and (3) the tendency to produce discomfort. A description of tests designed especially for the investigation of these

effects has already appeared in print.[1] The test for the second effect, it may be mentioned, is not analytical in nature. Its results express an aggregate loss of function. Supplementary tests have been devised, therefore, by means of which the factors contributive to a given result may be separated out. A description of these tests is also included in the papers referred to above.

The following aspects of lighting sustain an important relation to the eye: the evenness of illumination, the diffuseness of light, the angle at which the light falls on the object viewed, the evenness of surface brightness, intensity, and quality. The first four of these factors, which may be grouped together as distribution factors, will be discussed briefly with reference to types of lighting now in common use.

The ideal condition with regard to the distribution factor is to have the field of vision uniformly illuminated with light well diffused and no extremes of surface brightness. When this condition is attained the illumination of the retina will shade off more or less gradually from center to periphery, which gradation is necessary for accurate and comfortable fixation and accommodation. In the proper illumination of a room by daylight, we have been able thus far to get the best conditions of distribution. Before it reaches our windows or skylights, daylight has been rendered widely diffuse by innumerable reflections; and the windows and skylights themselves acting as sources have a broad area and low intrinsic brilliancy, all of which features contribute towards giving the ideal conditions of distribution stated above. Of the systems of artificial lighting the best distribution effects, speaking in general terms, are given by the indirect systems, and the semi-indirect systems with a small direct component of light. In the indirect systems the

[1] Ferree, C. E. "Tests for the Efficiency of the Eye under Different Systems of Illumination and a Preliminary Study of the Causes of Discomfort," *Trans. Ill. Eng. Soc.* 1913, *8*, pp. 40–60; "Untersuchungsmethoden für die Leistungsfähigkeit des Auges bei verschiedenen Beleuchtungssystemen, und eine vorläufige Untersuchung über die Ursachen unangenehmer optischer Empfindungen," *Z. f. Sinnesphysiol.*, 1915, *49*, pp. 59–78; "The Efficiency of the Eye under Different Systems of Lighting," *Fourth Intern. Congress on School Hygiene*, Buffalo, 1913, *5*, pp. 351–364; "Ophthalmology," July, 1914, pp. 1–16; "Mind and Body," 1913, *20*, pp. 280–286, 345–353; "The Problem of Lighting in Its Relation to the Efficiency of the Eye," *Science*, July 17, 1914, N. S., *15*, pp. 84–91; Ferree, C. E. and Rand, G. "The Efficiency of the Eye under Different Conditions of Lighting: The Effect of Varying Distribution and Intensity," *Trans. Illum. Eng. Soc.*, August, 1915, *10*, pp. 407–447; "Further Experiments on the Efficiency of the Eye under Conditions of Lighting," *Trans. Ill. Eng. Soc.*, August, 1915, *15*, pp. 448–504. See also J. R. Cravath. "Some Experiments with the Ferree Test for Eye Fatigue," *Trans. Ill Eng. Soc., 1914, 9,* pp. 1033–1047; also C. E. Ferree, "Discussion of Mr. Cravath's Paper, Some Experiments," etc., *ibid.*, pp. 1050–1059.

source is concealed from the eye and the light is thrown against the ceiling or some other diffusely reflecting surface in such a way that it suffers one or more reflections before it reaches the eye. In some of the respects most important to the eye, this and the semi-indirect systems with a small direct component of light give the best approximation of the distribution effects characteristic of daylight of any that have yet been devised. The direct lighting systems are designed to send the light directly to the plane of work. There is in general in the use of these systems a tendency to concentrate the light on the working plane or object viewed rather than to diffuse it, and to emphasize brightness extremes rather than to level them down. Too often, too, the eye is not properly shielded from the light source and frequently no attempt at all is made to do this. The semi-indirect systems are intended to represent a compromise between the direct and indirect systems. A part of the light is transmitted directly to the plane of work through the translucent reflector placed beneath the source of light, and a part is reflected to the ceiling. Thus, depending upon the density of the reflector, this type of system may vary between the totally direct and the totally indirect as extremes and share in the relative merits and demerits of each in proportion to its place in the scale. By giving better distribution effects this type of system is supposed also to be a concession to the welfare of the eye, but our tests show that the concession, at least for the reflectors of low and medium densities, is not so great as it is supposed to be. In fact, installed at the intensity of illumination ordinarily used or at an intensity great enough for all kinds of work, little advantage seems to be gained for the eye in this type of lighting with reflectors of low or medium densities; for with these intensities of light and densities of reflector, the brightness of the source has not been sufficiently reduced to give much relief to the suffering eye. Until this is done in home, office, and public lighting, we can not hope to get rid of eye strain with its complex train of physical and mental disturbances.

In the experimental work the following points are covered: the effect of varying the distribution factors on the ability of the eye to maintain its maximal efficiency for a period of work; the effect of varying the intensity of light with various groupings of distribution factors; and certain miscellaneous experiments relating to the hygienic employment of the eye. These latter experiments include the effect of varying the area and conversely the intrinsic brightness of the ceiling spots above the reflectors in an indirect system of lighting; the effect of varying the angle at which the light falls on the work in a given lighting situation; the effect of

using an opaque eye-shade with light and dark linings with each of the lighting installations used in the distribution and intensity series; the effect on the efficiency of the fixation muscles of a period of work under each of these installations; the effect of motion pictures on the eye at different distances from the projection screen; and a determination of the tendency of all the conditions of lighting employed to produce discomfort and to cause loss of efficiency.

The investigations are not abstract in character. All the variations obtained were gotten in actual concrete lighting situations by employing lighting installations in common use. In order that a correlation might be made between lighting conditions and the effect on the eye, the following specification of illumination effects was made in each case. (1) A determination was made of the average illumination of the room under each of the installations of lighting used. The room was laid out in 3-ft. squares and illumination measurements were made at 66 of the intersections of these squares and at the point of work. Readings were taken in a plane 122 cm. above the floor with the receiving test-plate of the illuminometer in the horizontal, the 45 deg., and the 90 deg. positions, measuring respectively the vertical, the horizontal, and the 45 deg. components of illumination. The 122 cm. plane was chosen because that was the height of the test object. In the work on the distribution series the illumination was made as nearly as possible equal at the point of work. (2) A determination was made in candle-power per sq. in. of the brightness of prominent objects in the room, such as the test surface; the reflectors for the semi-indirect installation; the reflectors and filament for the direct installation, etc.; the reading-page; the specular reflection from surfaces; etc. The brightness measurements were made by means of a Sharp-Millar illuminometer with the test-plate removed. The instrument was calibrated against a magnesium oxide surface obtained by depositing the oxide from the burning metal. By this method the reflecting surfaces were used as detached test-plates. The readings were converted into candle-power per sq. in. by the following formula:

$$\text{Brightness} = \frac{\text{Foot-candles}}{\pi \times 144}$$

(3) Photographs were made of the room from three positions under each system of illumination.

The tests for the effect on the eye were made at four representative positions in the room. The observers used were all under 26 years of age. A clinic record was made of the eyes of each observer. The following results were obtained.

1. Of the lighting factors that influence the welfare of the eye

those we have grouped under the heading of distribution are apparently fundamental. They seem to be the most important we have yet to deal with in our search for the conditions that give us the minimum loss of efficiency and the maximum comfort in seeing. If, for example, the light is well distributed in the field of vision, and diffuse, and there are no extremes of surface brightness, our tests indicate that the eye, so far as the problem of lighting is concerned, is practically independent of intensity. That is, when the proper distribution effects are obtained, intensities high enough to give the maximum discrimination of detail may be employed without causing appreciable damage or discomfort to the eye.

2. For the kind of distribution effects given by the direct and semi-indirect reflectors of low or medium densities, our results show that unquestionably too much light is being used in ordinary work for the comfort and welfare of the eye.

3. The angle at which the light falls on the object viewed is an important factor, but not nearly so important, for example, as evenness of surface brightness in the field of vision. Extremes of surface brightness in the field of vision seem to be the most important cause of the eye's discomfort and loss of efficiency in lighting systems as we have them at the present time. In lighting from exposed sources it is not infrequent to find the brightest surface from 1,000,000 to 2,500,000 times as brilliant as the darkest; and from 300,000 to 600,000 times as brilliant as the reading-page. These extremes of brightness in the field of vision are, our tests show, very damaging to the eye.

4. Of the systems of artificial lighting tested thus far, the best results have been obtained for the indirect system, and the semi-indirect systems with reflectors having a high density. By means of these reflectors the light is well distributed in the field of vision and extremes of surface brilliancy are kept within the limits which the eyes are prepared to stand. Considerable loss of efficiency has been found to result from the use of direct reflectors and semi-indirect reflectors of low or medium density.

5. The loss of efficiency sustained by the eye under an unfavorable lighting situation is found to be muscular, not retinal. The retina has been found to lose little if any more in efficiency under one than under another of the lighting systems employed.

6. Loss of efficiency of the fixation muscles is, according to our tests, a very small part of the eye's aggregate loss in muscular efficiency as the result of work under an unfavorable lighting system. The chief loss seems to be sustained by the accommodation muscles or the muscles which adjust the lens of the eye.

7. Eye-shades are apparently not an adequate substitute for

lamp-shades for the protection of the eye from the sources of light. The best results are obtained by means of an opaque eye-shade with a light lining. The usual opaque eye-shades with dark linings, while they shield the eye from the source of light, do not by any means eliminate harmful brightness differences in the field of vision. They in fact create for the eye a very unnatural brightness relation; *i. e.*, they make the whole upper half of the field of vision dark in sharp contrast with the brightly lighted lower half. The direct effect of this is a strong brightness contrast (physiological) over the lower half of the field of vision which causes glare in surfaces which have no glare and increases the glare in surfaces in which glare is already present. Moreover, the unusual and strongly irregular character of the image formed on the retina probably also sets up warfare in the incentives given to the muscles which adjust the eye. That is, the upper half of the field of vision is dark and presents no detail. The effect of this is probably to exert a tendency to cause the muscular relaxation characteristic of the darkened field of vision. The lower half of the field of vision is light and filled with detail. The incentive here is for the best possible adjustment of the eye for the discrimination of detail in the objects viewed, while the rim of the shade, the sharply marked boundary between the light and dark halves of the field of vision and much nearer to the eye than the objects viewed, serves as a constant and consciously annoying distraction to fixation and accommodation These complex and somewhat contradictory impulses given to th muscles of the eye might very well and doubtless do cause an ex cessive and unnatural loss of energy and efficiency in case of th prolonged adjustment of the eye needed for a period of work Translucent shades when made sufficiently opaque to give the neces sary reduction to the image of the source, darken too much th upper half of the field of vision and simulate thereby too much th effect given by the opaque shade with the dark lining to give th best results for efficient and comfortable seeing.

8. The observation of motion pictures for two or more hour causes the eye to lose heavily in efficiency. The loss decrease rather regularly with the increase of distance from the projectio screen. It seems little if any greater, however, than the loss cause by an equal period of working under much of the artificial ligh ing now in actual use. In making these tests care was taken t choose a projection apparatus which gave a picture comparativel steady and free from flicker.

9. In all the conditions tested a rather close correlation is foun

to obtain between the tendency of a given lighting condition to cause loss of efficiency and to produce discomfort.

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SOME EXPERIMENTS ON THE EYE WITH INVERTED REFLECTORS OF DIFFERENT DENSITIES.*

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Synopsis: In previous papers read before this society by the present writers, the gradation of surface brightness and its distribution in the field of vision were shown to be important factors in the effect of lighting conditions on the eye. In the work described in the present paper, gradation of surface brightness is made the chief variable. Inverted reflectors of six degrees of density are employed, and a correlation is made between the illuminating effects obtained and the tendency to cause loss of power to sustain clear seeing and to produce ocular discomfort.

INTRODUCTION.

This paper is the fourth in a series in which the effect of different conditions of lighting on the eye is investigated. In the first paper, two tests were described—one designed to be used as a general test for detecting the comparative tendencies of different lighting conditions to cause a loss in the eye's power to sustain clear seeing for a period of work; the other for detecting the tendency to produce ocular discomfort. In the second paper, the application of the first of these tests to various lighting conditions was begun. Two purposes were had in making this application: (1) the studying and perfecting of the test itself for use in lighting work, which it is obvious could not be done effectively under one set or type of lighting conditions;[1] and (2), the investigation of pertinent lighting effects, the results of which could be made both to serve as a guide for further work, and to provide cumulative data from which conclusions may be drawn as the conditions and stage of advancement of the work may warrant. This paper was divided into two sections. In the first the test was applied to the determination of the effect on the eye of three lighting installations, direct, semi-indirect and indirect, so selected as to give wide differences in illuminating effects. In the second section the effect of six variations in intensity for the direct and semi-indirect installations was determined. In both

* A paper presented at the ninth annual convention of the Illuminating Engineering Society, Washington, D. C., September 20-23, 1915.

of these cases the tests were all made at one position in the room, the point marked as the position of the observer in Fig. 1 of the present paper. Obviously, however, the effect of an unfavorable installation on the eye will vary with the position of the observer in the room. In the third paper, therefore, the tests were repeated for these installations at four positions in the room: the first with six reflectors in the field of view; the second with four; the third with two, and the fourth with none. The following features were also included: the work of the intensity series was completed, *i. e.,* six intensities of light were used with the indirect reflectors; a test was described for determining the effect on the fixation muscles of the eye; and a series of miscellaneous experiments was conducted pertaining to the hygienic employment of the eye. In these experiments the following points were taken up: the effect of varying the area, and conversely the intrinsic brilliancy of the ceiling spots above the reflectors of the indirect system of lighting used; the effect of varying the angle at which the light falls on the work in a given lighting situation; the effect of using an opaque eye-shade with dark and light linings with a number of lighting installations; the effect on the efficiency of the fixation muscles of three hours of work under each of these installations; the effect of motion pictures on the eye for different distances of the observer from the projection screen; and a determination of the tendency of the different conditions of lighting used in these experiments to produce ocular discomfort, and a comparison of the tendency to produce discomfort and to cause loss of efficiency.

Time cannot be taken here even for a brief statement of the results obtained in these experiments. For the purpose of this paper, it will be sufficient to say that gradation of surface brightness and its distribution in the field of vision were shown to be important factors in the effect on the eye. In the work to be described in the present paper, gradation of surface brightness has been made the chief variable. Inverted opal glass reflectors of six degrees of density have been employed and a correlation has been obtained between the illuminating effects produced and their tendency to cause loss of efficiency and to produce ocular discomfort. As the work progresses, an attempt will be made

not only to investigate this factor further in some of its more important relations to lighting practise, but to take up in turn, so far as is practicable, each of the other factors mentioned in the former papers.[2]

CONDITIONS TESTED

An effort has been made to get a series of reflectors similar in size and shape and differing only in density. It is our ultimate purpose to use these reflectors both in accord with the principles of direct and indirect lighting, and by employing additional translucent and opaque reflectors, differing if need be in size and shape, to vary first one and then the other of the distribution factors mentioned in the former papers. So far, however, we have been able to use only six of the number of reflectors needed to carry out this plan, and these in accord with the principle of indirect lighting. They were all turned towards the ceiling and were installed the same distance from it. So installed, as the photometric measurements will show, the chief variables have been the brightness of the reflectors and the ceiling spots above the reflectors,—more especially, the brightness of the reflectors. The reflectors used will be designated here by the numerals, I, II, III, IV, V and VI; and will be described in greater detail in an appendix to the paper. They were all installed 30 in. (0.76 m.) from the ceiling[3] and were held by Plume and Atwood semi-indirect holders attached to cords dropped from the eight outlets shown in Fig. 1.

It has been our wish to conduct this investigation, as has been the case in all our work on the distribution factors, with the quality and intensity of the light made approximately the same. Unfortunately, with the material available, the quality of the light could not be made in all cases uniformly alike. Clear tungsten lamps were used as light sources with each installation, but two of the reflectors, I and II, were not free from color. The density of these reflectors had been secured in part, by giving them a brownish tone. Just how much effect this would have, if any, on the results of the tests we are not prepared at this time to say. The fact should be borne in mind, however, in considering the results obtained. It was decided to make the intensity of light as nearly equal as possible at the test object and to give a

supplementary specification of the lighting effects in the remainder of the room.

At the test object the light was photometered in several directions. It was made approximately equal in the plane of the test object and as nearly as possible equal in the other directions. The specification of the lighting effects in the remainder of the room was accomplished as follows. (1) A determination was made of the average illumination of the room under each set of reflectors. The room was laid out in 3 ft. (0.90 m.) squares and

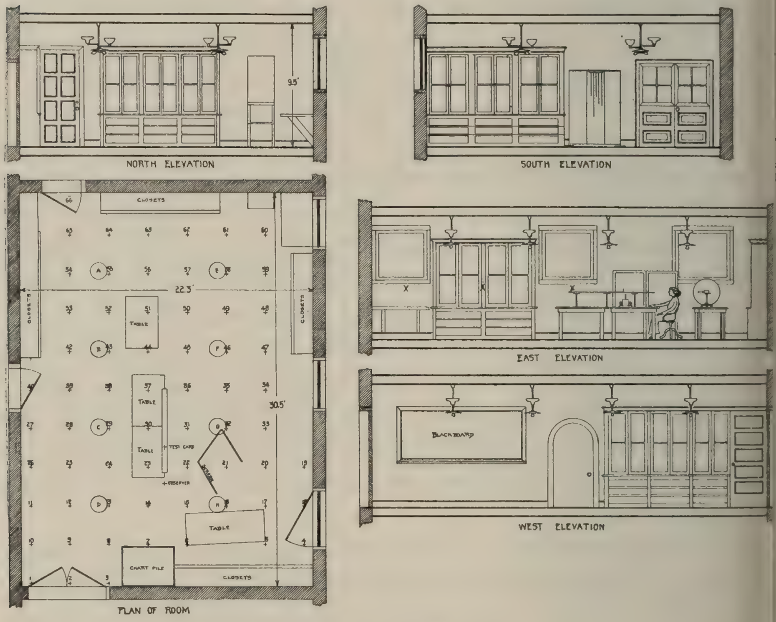


Fig. 1.—Plan of test room.

illumination measurements were made at 66 of the intersection of the sides of these squares. Readings were taken in a plan 122 cm. above the floor with the receiving test-plate of the illuminometer in the horizontal, the 45° and 90° positions, measurin respectively, the vertical, the 45° and horizontal components o illumination. The 122 cm. plane was chosen because that was th height of the test object. (2) A determination was made of th brightness of prominent objects in the room, such as the tes card, the reflectors, the reading page, the specular reflection fron

surfaces, etc. The brightness measurements were made by means of a Sharp-Millar photometer with the receiving test-plate removed. The instrument was calibrated against a magnesium oxide surface obtained by depositing the oxide from the burning metal on a white card. By this method the reflecting surfaces were used as detached test-plates. The readings were converted into candlepower per square inch by the following formula: brightness = foot-candles/$\pi \times 144$. (3) Photographs were made of the room for each set of reflectors employed. They will not all be included in this paper, however, because too little difference in illuminating effects is shown for the different reflectors to warrant so extensive a use of the photographic method of specification.

The tests were conducted in a room 30.5 ft. (9.29 m.) long, 22.3 ft. (6.797 m.) wide, and 9.5 ft. (2.895 m.) high. In Fig. 1, this room is shown drawn to scale: plan of room, north, south, east and west elevations. In the plan of room are shown the 66 stations at which the illumination measurements were made; and the positions of the outlets for the lighting fixtures, A, B, C, D, E, F, G and H. In the drawing, east elevation, the position of the observer at which the tests were taken is represented.[4] So far in the work with these reflectors the tests have been made at only one point in the room.

Table I gives the illumination measurements for each of the 66 stations represented in Fig. I. These measurements were made with the receiving test-plate of the illuminometer in the horizontal, the vertical and the 45° planes. Tables II and III have been compiled to supplement Table I for the purpose of making a comparative showing of the evenness of illumination at the 122-cm. level given by the six sets of reflectors. Two cases may be made of this: (1) a comparison may be made of a given component from station to station; or (2) the difference between the components may be compared. To facilitate these comparisons (*a*) the mean variation from the average of each of the components has been computed; and (*b*) the difference in the average of the three components has been determined. Results for the first of these points are shown in Table II; and for the second in Table III.

TABLE I.

Showing the illumination measurements in foot-candles for each of the 66 stations represented in Fig. 1 for the six types of reflectors used.

Division A.

Station	Horizontal, reflector type I	II	III	Vertical, reflector type I	II	III	45°, reflector type I	II	III
1	1.40	1.35	1.30						
2	1.50	1.28	1.20						
3	1.49	1.52	1.27						
4	1.85	1.46	1.47						
5	2.40	2.20	2.0						
6	2.20	2.40	2.10						
7	2.60	2.50	2.30						
8	2.90	3.10	2.90						
9	2.70	2.60	2.50						
10	1.54	1.41	1.32						
11	2.10	1.88	1.78						
12	3.90	4.30	3.70	0.55	0.53	0.50	2.10	2.0	1.72
13	4.50	4.90	4.50	0.58	0.55	0.49	2.30	2.70	2.40
14	3.20	3.40	3.50	0.50	0.46	0.48	1.65	1.70	1.90
15	3.10	3.10	3.20	0.52	0.40	0.42	1.62	1.70	1.69
16	4.50	4.40	4.30	0.50	0.41	0.50	2.50	2.20	2.10
17	3.80	3.10	3.10	0.54	0.40	0.43	2.20	1.48	1.62
18	2.60	1.86	1.90	0.57	0.46	0.45	1.50	1.10	0.97
19	3.30	2.40	2.50	1.25	0.87	0.93	2.40	1.60	1.90
20	4.10	3.70	3.70	1.17	1.0	0.94	2.70	2.20	2.20
21	5.20	4.60	4.50	1.30	1.30	1.22	3.10	2.90	2.70
22	4.0	3.50	3.80	1.16	1.0	0.94	2.50	2.20	2.30
23	4.0	3.70	3 70	1.10	1.06	1.20	2.60	2.30	2.10
24	4.90	4.90	4.70	1.1	1.20	0.97	3.0	2.70	2.80
25	3.90	4.10	4.20	1.03	0.91	0.95	2.40	2.30	3.30
26	2.50	2.10	1.78						
27	2.80	2.80	2.40						
28	4.80	5.85	4.70	1.15	1.05	1.20	3.40	3.0	3.20
29	5.80	6.0	6.20	1.34	1.35	1.25	3.80	4.0	4.0
30	4.50	3.80	4.50	1.42	1.11	1.37	3.40	2.70	3.10
31	4.50	3.90	4.60	1.42	1.15	1.14	3.30	2.50	3.0
32	5.60	5.30	5.60	1.42	1.33	1.32	4.0	3.70	3.40
33	5.0	3.60	4.25	1.52	1.10	1.15	3.30	2.60	2.80
34	4.70	3.80	3.80	1.86	1.54	1.42	3.70	2.90	2.80
35	5.20	4.90	5.0	2.10	1.64	1.60	4.40	3.50	3.80
36	4.50	4.10	4.50	1.80	1.61	1.48	3.60	2.80	3.30
37	4.60	4.0	4.60	1.99	1.54	1.66	3.70	3.0	3.50
38	4.90	5.40	5.40	2.0	1.90	1.80	4.0	3.80	4.20
39	4.10	4.10	4.0	1.72	1.68	1.50	3.20	3.10	3.20
40	2.60	2.40	2.0						
41	2.0	1.67	1.62						

TABLE I.—(*Continued.*)

Station	Horizontal, reflector type I	II	III	Vertical, reflector type I	II	III	45°, reflector type I	II	III
42	3.90	4.40	4.40	1.80	1.60	1.64	3.40	3.20	3.40
43	5.40	5.40	5.60	2.20	1.86	1.84	4.70	4.0	4.40
44	4.40	4.10	3.70	2.10	1.76	1.50	4.0	3.40	3.20
45	4.10	4.30	4.20	2.10	1.71	1.68	3.80	3.40	3.30
46	5.20	5.60	5.70	2.10	1.60	1.68	4.60	4.10	4.40
47	4.50	4.20	4.50	1.76	1.58	1.52	3.60	3.30	3.30
48	3.90	3.70	3.80	2.0	1.94	1.76	3.60	3.30	3.30
49	4.90	4.80	5.10	2.30	2.10	2.0	3.90	4.20	3.80
50	4.10	3.60	4.0	2.30	2.0	2.10	3.80	3.50	3.40
51	3.90	3.70	3.90	2.30	1.90	1.98	3.70	3.30	3.50
52	4.40	4.50	4.60	2.30	1.95	2.0	4.10	3.70	3.90
53	3.60	3.70	3.80	2.0	1.58	1.80	3.30	3.20	3.20
54	3.10	3.50	3.40	1.70	1.48	1.46	3.20	2.90	3.10
55	4.10	4.30	4.10	2.30	1.70	1.80	4.20	3.80	3.70
56	3.60	3.0	3.30	2.10	1.80	1.86	3.50	3.10	3.60
57	3.60	3.0	3.80	2.30	1.82	2.0	3.50	3.0	3.70
58	4.40	4.40	5.40	2.10	2.10	2.10	4.20	4.10	4.40
59	3.30	3.60	3.60	1.63	1.85	1.66	3.0	3.20	3.20
60	3.0	2.60	2.90	2.0	1.90	1.66	3.50	3.10	3.20
61	3.10	2.90	3.20	2.50	2.0	2.0	3.90	3.60	3.90
62	2.60	2.60	2.50	2.20	2.10	1.92	3.50	3.40	3.20
63	2.50	2.50	2.10	2.20	2.15	2.60	3.40	3.40	3.10
64	3.10	2.30	3.0	2.40	2.0	2.10	4.0	3.30	3.60
65	2.40	2.40	2.30	1.98	1.65	1.59	3.10	2.70	2.80
66	1.23	1.25	1.20						
Average	3.61	3.45	3.49	1.65	1.44	1.43	3.31	2.98	3.05

Division B.

Station	Horizontal, reflector type IV	V	VI	Vertical, reflector type IV	V	VI	45° reflector type IV	V	VI
1	1.50	1.45	1.37						
2	1.32	1.36	1.30						
3	1.42	1.40	1.35						
4	1.50	1.53	1.58						
5	2.30	2.50	2.40						
6	2.70	2.30	2.40						
7	2.60	2.60	2.50						
8	3.40	3.60	3.30						
9	2.80	2.80	2.80						
10	1.55	1.48	1.56						
11	2.00	1.94	2.00						
12	4.20	4.30	4.10	0.65	0.51	0.53	2.60	2.40	2.10
13	4.70	5.40	4.90	0.59	0.58	0.60	2.90	3.10	2.90
14	3.60	3.40	3.60	0.56	0.49	0.50	1.88	1.88	1.92

TABLE I.—(*Continued.*)

Station	Horizontal, reflector type			Vertical, reflector type			45°, reflector type		
	IV	V	VI	IV	V	VI	IV	V	VI
15	3.10	3.40	3.30	0.58	0.49	0.43	1.72	1.80	1.80
16	4.40	4.70	4.80	0.55	0.40	0.56	2.30	2.70	2.60
17	3.10	3.60	3.70	0.44	0.43	0.50	1.64	1.85	2.0
18	1.88	1.96	2.0	0.49	0.51	0.57	1.14	1.15	1.15
19	2.75	2.60	2.80	1.25	1.10	1.13	2.10	1.88	1.84
20	4.20	3.80	4.30	1.20	1.20	1.18	2.70	2.30	2.60
21	4.60	5.0	5.0	1.22	1.48	1.36	2.80	2.50	3.20
22	3.70	3.80	4.10	1.18	1.05	1.04	2.50	2.40	2.50
23	3.80	4.40	4.20	1.15	1.26	1.06	2.30	2.70	2.50
24	5.20	5.90	5.70	1.47	1.52	1.27	3.20	3.30	3.0
25	4.90	4.50	4.30	1.25	1.31	1.07	2.90	2.80	2.40
26	2.40	2.50	2.20						
27	2.70	2.80	2.75						
28	5.10	4.90	5.20	1.45	1.24	1.14	3.80	3.40	3.60
29	5.60	6.10	6.40	1.54	1.34	1.35	4.30	4.40	4.60
30	4.30	4.30	4.50	1.37	1.27	1.36	3.20	3.0	3.50
31	4.20	4.0	4.40	1.30	1.26	1.30	3.0	2.90	3.30
32	5.60	5.80	6.20	1.38	1.40	1.53	3.70	4.25	4.5
33	4.10	4.50	4.80	1.42	1.28	1.38	3.10	3.40	3.80
34	4.0	4.0	4.20	1.80	2.0	1.88	3.0	3.30	3.50
35	5.40	5.60	5.80	2.10	2.20	2.40	4.0	4.0	4.40
36	4.40	4.30	4.50	1.70	2.0	1.98	3.40	3.50	3.60
37	4.30	4.40	4.30	1.88	1.96	1.92	3.40	3.30	3.50
38	5.20	5.0	5.50	2.30	2.30	2.20	4.60	4.10	4.40
39	4.30	4.20	4.50	2.20	1.68	1.90	3.80	3.30	3.70
40	2.60	2.40	2.60						
41	1.80	1.81	1.92						
42	4.50	4.20	4.40	1.82	1.90	1.85	3.50	3.60	3.80
43	5.40	5.50	5.80	2.10	2.10	2.10	4.50	4.30	4.80
44	3.80	3.70	4.50	1.90	2.10	2.0	3.30	2.70	3.90
45	4.20	4.40	4.60	1.90	1.90	1.98	3.60	3.90	3.90
46	5.40	5.80	6.20	1.90	1.85	1.88	4.30	4.70	4.60
47	3.90	4.0	4.50	1.80	1.78	1.72	3.60	3.30	3.80
48	3.60	3.70	4.50	1.91	1.94	2.30	3.20	3.30	4.0
49	5.0	4.90	5.30	2.20	2.60	2.60	4.50	4.60	4.80
50	3.90	4.0	4.20	2.40	2.20	2.80	3.70	3.70	4.20
51	3.90	3.80	4.20	2.40	2.20	2.60	3.70	3.60	4.10
52	4.65	4.70	5.0	2.50	2.50	2.50	4.10	4.20	4.20
53	4.0	3.50	4.0	2.10	2.10	2.10	3.50	3.20	3.60
54	3.70	3.50	3.80	1.74	1.70	1.82	3.20	3.30	3.60
55	4.20	4.70	5.0	2.40	2.0	2.20	4.0	4.30	4.90
56	3.20	3.30	3.60	2.20	2.20	2.10	3.50	3.60	3.90
57	3.40	3.50	3.60	2.20	2.30	2.20	3.60	3.80	3.70
58	4.60	5.10	5.20	2.20	2.30	2.40	4.20	4.90	4.60

TABLE I.—(*Continued.*)

Station	Horizontal, reflector type IV	V	VI	Vertical, reflector type IV	V	VI	45°, reflector type IV	V	VI
59	3.90	3.90	4.30	1.78	1.81	2.40	3.20	3.50	4.0
60	2.50	2.50	3.0	2.0	2.20	2.40	3.30	3.70	3.80
61	3.20	3.20	3.80	2.30	2.60	2.40	4.40	4.20	4.6
62	2.30	2.60	2.50	2.10	2.30	2.40	3.20	3.0	3.40
63	2.50	2.40	2.60	2.60	2.80	2.10	3.60	3.80	3.40
64	3.10	2.90	3.0	2.30	2.40	2.40	4.0	4.0	4.0
65	2.30	2.40	2.40	2.0	2.0	2.10	3.10	3.00	3.10
66	1.14	1.16	1.42						
Average	3.80	3.70	4.20	1.675	1.68	1.71	3.30	3.31	3.49

TABLE II.

Compiled from Table I to show a comparison of the evenness of the illumination at the 122-cm. level given by the six types of reflector used.

Type of reflector	Mean variation of components: Vertical	Horizontal	45°	Percentage of mean variation of components: Vertical	Horizontal	45°
I	0.976	0.516	0.582	27.0	31.3	17.6
II	0.999	0.487	0.576	29.0	33.8	19.3
III	1.066	0.430	0.562	30.5	30.1	18.4
IV	1.21	0.498	0.601	31.8	29.7	18.2
V	1.10	0.539	0.628	29.8	32.1	19.0
VI	1.47	0.574	0.677	35.0	31.2	19.4

TABLE III.

Compiled from Table I to show the difference in the average values of the three components of illumination for the six types of reflector used.

Type of reflector	Difference between components: Vertical and horizontal	Vertical and 45°	45° and horizontal	Percentage of difference between components: Vertical and horizontal	Vertical and 45°	45° and horizontal
I	1.96	0.30	1.66	54.3	8.3	50.2
II	2.01	0.47	1.54	58.3	13.6	51.7
III	2.06	0.44	1.62	59.0	12.6	53.1
IV	2.125	0.50	1.625	55.9	13.2	49.2
V	2.02	0.39	1.63	54.6	10.5	49.2
VI	2.49	0.71	1.78	59.3	16.9	51.0

Figs. 2-5 are taken from the series of photographs showing the illumination effects produced by the six types of reflector used.[5] As was stated earlier in the paper, not so much use has been made of the photographic method of specification in this as in the former papers. In the former papers three photographs were given for each set of reflectors. One of these was taken from the south end of the room at a point 4 ft. (1.22 m.) from the

west wall. This photograph was taken so as to comprehend as much of the room as was possible in one view. It included the greater part of the ceiling, floor, and north wall, six of the fixtures and about one-half of the east wall. Another was taken to show the illumination effects in the west half of the room. This photograph represents the distribution of light and shade on the greater part of the west wall and adjacent ceiling and includes two of the fixtures. A third was taken primarily for showing the brightness measurements of all surfaces having a very high or very low brilliancy in the field of view of the observer. To have carried out this program in full in the present work would have required the insertion here of eighteen photographs. The amount of difference in the distribution of light and shade for the different reflectors was much too small to warrant this. It has in fact been deemed sufficient to include in this paper photographs for only the second and third of these positions and for only two of the sets of reflectors used,—the most opaque and the least opaque. The photographs for the second position are shown in Figs. 2 and 3; for the third, in 4 and 5. In representing the brightness measurements in Figs. 4 and 5, the spot measured is marked by a letter and the numerical value of the brightness measurement in candle-power per square inch is printed near by. The spots are lettered for convenience of reference in the tables of brightness measurements. The photographs were taken from a point directly behind the position of the observer as near to the south wall of the room as was possible; and although not all of the observer's field of view is covered by the brightness measurements made, owing to the narrow field of the camera as compared with the binocular field, still the order of magnitude of brightness differences present in the field of view is well represented by these measurements.

In Tables IV and V are given the brightness measurements of the room for the six sets of reflectors. These tables also include the letters identifying the measurements with the spots measured as shown in Figs. 4 and 5. The distribution of light and shade in the room was so similar for the different sets of reflectors that the spots measured have approximately the same location for each set of reflectors. Two sets of measurements were made of the brightness of the reflectors,—one with the opening of the

Fig. 2.—Showing the illumination of the west wall of the room, Reflector I.

Fig. 3.—Showing the illumination of the west wall of the room, Reflector VI.

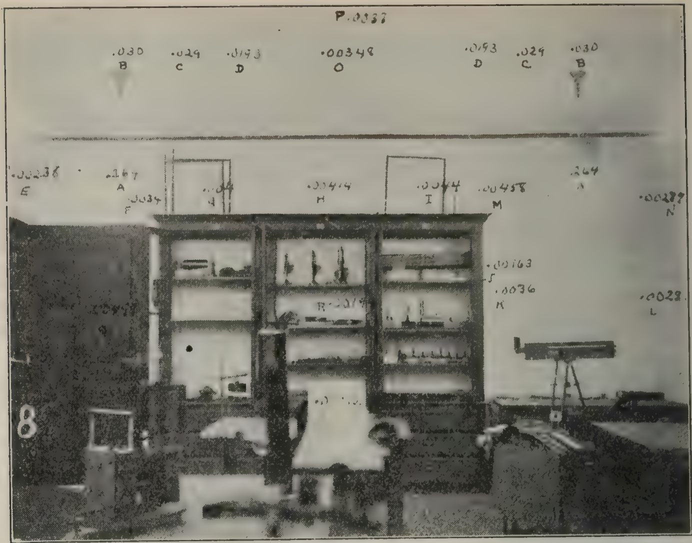


Fig. 4.—Showing the illumination effects in the north end of the room, Reflector I; and the brightness measurements of all surfaces having a very high or a very low brilliancy. This photograph was taken from a point directly behind the observer as near to the south wall of the room as was possible, and comprehends as much of the observer's field of view as could be included in the field of the camera.

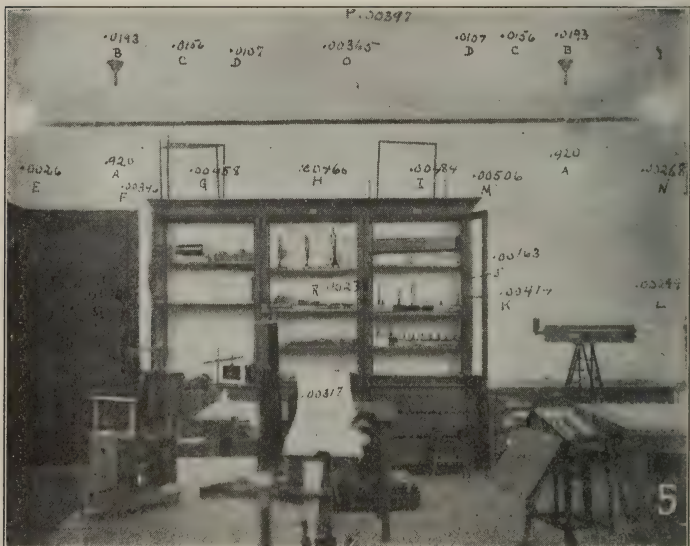


Fig. 5.—Showing the illumination effects in the north end of the room, Reflector VI; and the brightness measurements of all surfaces having a very high or a very low brilliancy. This photograph was taken from a point directly behind the observer as near to the south wall of the room as was possible, and comprehends as much of the observer's field of view as could be included in the field of the camera.

illuminometer close to the reflector and the other with the opening as nearly as possible in the position of the observer when making the test. In the former case the receiving arm was turned normal to the surface measured and the instrument was supported in such a position that the opening was about 4 in. (10.16 cm.) from this surface. The surfaces of some of the reflectors presented so much unevenness of brightness that overlapping measurements were made and an average taken. These average values are given in Table IV. In Table V is given the brightness of the reflectors as measured from the position of the observer. These measurements were taken of the reflectors at outlets A, B and C (Fig. 1) for each of the six installations. A comparison of these measurements will show that reflector B has in each case a higher value than reflector A, and C a higher value than B. Whether or not this can be wholly accounted for because the reflectors were not perfect diffusers we are not prepared to say. That is, the angle subtended by reflector A at the point of observation was less than that subtended by B, and by B less than that subtended by C; so that at the distance at which these reflectors was viewed approximately all of A occupied the field of the illuminometer in making the brightness match, while only the brighter central portions of B and C were comprehended in this field, still less of the duller periphery being included for C than for B.

In Tables VI and VII, are shown some prominent ratios of surface brightness for the six sets of reflectors. In compiling these ratios it has been considered important to make a comparative showing for the different types of reflectors (*a*) of the extremes of surface brightness and (*b*) of the relation of the brilliancy of objects in the surrounding field to the surface brightness at the point of work. Extremes of surface brightness are shown by giving the ratios between surfaces of the first, second, third, etc., order of brilliancy and the lowest order of brilliancy; and the comparison of the brilliancy of objects in the surrounding field to the brightness at the point of work by giving the ratios of the surfaces of the first, second, and third order of brilliancy to the brightness of the test card and the reading page in the working position.

TABLE IV.

Showing the brightness measurements in candlepower per square inch for the surfaces A, B, C, D, etc. (Figs. 4 and 5), the test card and reading page. These measurements were taken with the illuminometer close to the surface measured and with its receiving arm normal to this surface.

Surface measured	Reflector type I.	Reflector type II	Reflector type III	Reflector type IV	Reflector type V	Reflector type VI
A........	0.264	0.361	0.392	0.614	0.848	0.920
B........	0.030	0.01985	0.024	0.0101	0.0137	0.0193
C........	0.029	0.021	0.021	0.0123	0.0166	0.0156
D........	0.0193	0.0106	0.0075	0.0070	0.00767	0.0107
E........	0.00238	0.00246	0.00229	0.00282	0.00255	0.0026
F........	0.0034	0.00394	0.0034	0.00396	0.00396	0.00396
G........	0.0040	0.00392	0.0042	0.00497	0.00418	0.00458
H	0.00414	0.00396	0.0044	0.00506	0.0043	0.00466
I	0.0044	0.00402	0.00453	0.00528	0.0042	0.00484
J	0.00163	0.0011	0.00128	0.00141	0.00123	0.00163
K	0.0036	0.00387	0.00414	0.0044	0.00425	0.00414
L........	0.0023	0.00224	0.00282	0.00299	0.00273	0.00299
M	0.00458	0.00405	0.00484	0.0052	0.00427	0.00506
N........	0.00277	0.00216	0.00216	0.00334	0.00268	0.00268
O........	0.00348	0.00299	0.00462	0.00361	0.00361	0.00365
P	0.0037	0.00312	0.00506	0.00409	0.0037	0.00397
Q........	0.00097	0.00083	0.00106	0.00099	0.000924	0.00106
R........	0.00199	0.0029	0.00207	0.00220	0.00246	0.00238
Test card.	0.00312	0.00308	0.00308	0.00317	0.00312	0.00317
Reading page horizontal..	0.00528	0.00497	0.00506	0.0052	0.00484	0.00484
Reading page 45° position..	0.00352	0.00348	0.00352	0.00348	0.00334	0.00339

TABLE V.

Showing the brightness measurements in candlepower per square inch of the reflectors used when the measurements are made from the position occupied by the observer during the test. In these measurements the receiving arm of the illuminometer was placed as nearly as possible in the position of the observer's eye during the test, and was pointed at the reflector. The position of the reflector in each case is shown by the letters A, B and C in Fig. 1.

Position of reflector	Reflector type I	Reflector type II	Reflector type III	Reflector type IV	Reflector type V	Reflector type VI
A........	0.119	0.156	0.180	0.2325	0.327	0.382
B........	0.1755	0.1913	0.2025	0.2535	0.338	0.405
C........	0.2025	0.338	0.397	0.544	0.722	0.830

Supplementary to Tables IV, VI and VII we have computed for the six types of reflector the mean variation of the several brightness values from their average values. While important from the standpoint of showing the variations from the mean for the different types of reflector, such a comparison is, however, probably not so important from the standpoint of the eye as are the comparisons given in Tables IV to VII. That is, from the standpoint of the effect on the eye it is probably more important to give a representation of the brightness of individual surfaces, more especially of surfaces showing extremes of brightness, than it is to give the mean variation from the average brightness of all the surfaces. In order to make possible the comparison with and without the reflector and the spot above the reflector, the table is made to show separately the mean variation of the following measurements: (*a*) for all: (*b*) for all but the reflector; and (*c*) for all but the reflector and the spot above the reflector. Results are given in Table VIII.

As was stated earlier in the paper the effect of a harmful installation on the ability of the eye to maintain its efficiency for a period of work varies with the position of the observer in the room. In the former work the tests were made at four positions, one in which six fixtures were in the field of view; one in which four were in the field of view; one in which two were in the field of view; and one in which none was in the field of view. This variation of the position in which the observation is made accomplishes two purposes: (1) it gives us a more representative idea of the difference of the effect on the eye of the six types of lighting used; and (2) it shows the effect of varying the number of surfaces in the field of view showing brightness differences, particularly the number of primary sources. So far we have been able to conduct the tests for the reflectors used in this work at only one of these positions, namely, the one with six reflectors in the field of view.[6] Later we expect to repeat the tests for at least a part of these reflectors at the other three positions.

The results for the effect on the eye are given in Table IX.[7] The values given in this table are averaged in each case from the results of 6 three-hour tests and are typical of the results obtained for all of our observers. In order to show the repro-

TABLE VI.*

Ratios showing the extremes of surface brightness for the six types of reflectors used.

Division A.

Ratio	Reflector type I	Reflector type II	Reflector type III
Lightest to darkest	0.264 /0.00097 = 272.0	0.361 /0.00083 = 435.0	0.392 /0.00106 = 370.0
2nd lightest to darkest	0.030 /0.00097 = 31.0	0.021 /0.00083 = 25.3	0.024 /0.00106 = 22.6
3rd lightest to darkest	0.029 /0.00097 = 29.9	0.01985/0.00083 = 23.9	0.021 /0.00106 = 19.8
4th lightest to darkest	0.0193 /0.00097 = 20.0	0.0106 /0.00083 = 12.8	0.0075 /0.00106 = 7.08
5th lightest to darkest	0.00458/0.00097 = 4.72	0.00405/0.00083 = 4.88	0.00506/0.00106 = 4.77
6th lightest to darkest	0.0044 /0.00097 = 4.54	0.00402/0.00083 = 4.84	0.00484/0.00106 = 4.57
7th lightest to darkest	0.00414/0.00097 = 4.27	0.00396/0.00083 = 4.77	0.00462/0.00106 = 4.36
8th lightest to darkest	0.0040 /0.00097 = 4.12	0.00394/0.00083 = 4.75	0.00453/0.00106 = 4.27
9th lightest to darkest	0.0037 /0.00097 = 3.81	0.00392/0.00083 = 4.72	0.0044 /0.00106 = 4.15
10th lightest to darkest	0.0036 /0.00097 = 3.71	0.00387/0.00083 = 4.66	0.0042 /0.00106 = 3.96
11th lightest to darkest	0.00348/0.00097 = 3.59	0.00312/0.00083 = 3.76	0.00414/0.00106 = 3.91
12th lightest to darkest	0.0034 /0.00097 = 3.51	0.00299/0.00083 = 3.60	0.0034 /0.00106 = 3.21
13th lightest to darkest	0.00277/0.00097 = 2.86	0.0029 /0.00083 = 3.49	0.00282/0.00106 = 2.66
14th lightest to darkest	0.00238/0.00097 = 2.45	0.00246/0.00083 = 2.96	0.00229/0.00106 = 2.16
15th lightest to darkest	0.0023 /0.00097 = 2.37	0.00224/0.00083 = 2.70	0.00216/0.00106 = 2.04
16th lightest to darkest	0.00199/0.00097 = 2.05	0.00216/0.00083 = 2.60	0.00207/0.00106 = 1.95
17th lightest to darkest	0.00163/0.00097 = 1.68	0.0011 /0.00083 = 1.33	0.00128/0.00106 = 1.21

TABLE VI.

Division B.

Ratio	Reflector type IV	Reflector type V	Reflector type VI
Lightest to darkest	0.614 /0.00099 = 620.0	0.848 /0.000924 = 918.0	0.92 /0.00106 = 868.0
2nd lightest to darkest.........	0.0123 /0.00099 = 12.4	0.0166 /0.000924 = 18.0	0.0193 /0.00106 = 18.2
3rd lightest to darkest	0.0101 /0.00099 = 10.2	0.0137 /0.000924 = 14.8	0.0156 /0.00106 = 14.7
4th lightest to darkest	0.007 /0.00099 = 7.70	0.00767/0.000924 = 8.30	0.0107 /0.00106 = 10.1
5th lightest to darkest	0.00528/0.00099 = 5.33	0.0043 /0.000924 = 4.65	0.00506/0.00106 = 4.77
6th lightest to darkest	0.0052 /0.00099 = 5.25	0.00427/0.000924 = 4.62	0.00484/0.00106 = 4.57
7th lightest to darkest	0.00506/0.00099 = 5.11	0.00425/0.000924 = 4.60	0.00466/0.00106 = 4.40
8th lightest to darkest	0.00497/0.00099 = 5.02	0.0042 /0.000924 = 4.55	0.00458/0.00106 = 4.32
9th lightest to darkest	0.0044 /0.00099 = 4.44	0.00418/0.000924 = 4.52	0.00414/0.00106 = 3.91
10th lightest to darkest	0.00409/0.00099 = 4.13	0.00396/0.000924 = 4.29	0.00397/0.00106 = 3.74
11th lightest to darkest	0.00396/0.00099 = 4.0	0.0037 /0.000924 = 4.0	0.00396/0.00106 = 3.73
12th lightest to darkest	0.00361/0.00099 = 3.65	0.00361/0.000924 = 3.91	0.00365/0.00106 = 3.44
13th lightest to darkest	0.00334/0.00099 = 3.37	0.00273/0.000924 = 2.95	0.00299/0.00106 = 2.82
14th lightest to darkest	0.00299/0.00099 = 3.02	0.00268/0.000924 = 2.90	0.00268/0.00106 = 2.53
15th lightest to darkest	0.00282/0.00099 = 2.85	0.00255/0.000924 = 2.76	0.0026 /0.00106 = 2.45
16th lightest to darkest	0.0022 /0.00099 = 2.22	0.00246/0.000924 = 2.66	0.00238/0.00106 = 2.24
17th lightest to darkest	0.00141/0.00099 = 1.42	0.00123/0.000924 = 1.33	0.00163/0.00106 = 1.54

* It will be noted in Tables IV and VI that while the reflectors grade in brightness from I to VI in an unbroken series, the ratio lightest to darkest for Reflector III is less than for Reflector II, and for Reflector VI than for Reflector V. This in all probability is because of a difference in distribution effects given by these reflectors due to a difference in power to diffuse the light. That is, while the brightest spots (the reflectors) grade in an unbroken series, the darkest spots do not.

TABLE VII.

Ratios showing the relation of the brilliancy of objects in the surrounding field to the surface brightness at the point of work for the six types of reflector used.

Division A.

Ratio	Reflector type I	Reflector type II	Reflector type III
Lightest to test card	0.264 /0.00312 = 84.7	0.361 /0.00308 = 117.2	0.392 /0.00317 = 123.7
Lightest to reading page	0.264 /0.00352 = 75.0	0.361 /0.00348 = 103.8	0.392 /0.00348 = 112.6
2nd lightest to test card	0.030 /0.00312 = 9.61	0.021 /0.00308 = 6.8	0.024 /0.00317 = 7.57
2nd lightest to reading page	0.030 /0.00352 = 8.5	0.021 /0.00348 = 6.3	0.024 /0.00348 = 6.9
3rd lightest to test card	0.029 /0.00312 = 9.29	0.01985/0.00308 = 6.46	0.021 /0.00317 = 6.62
3rd lightest so reading page	0.029 /0.00352 = 8.2	0.01985/0.00348 = 5.70	0.021 /0.00348 = 6.03

Division B.

Ratio	Reflector type IV	Reflector type V	Reflector type VI
Lightest to test card	0.614 /0.00317 = 193.7	0.848 /0.00312 = 272.0	0.92 /0.00317 = 290.2
Lightest to reading page	0.614 /0.00348 = 176.4	0.848 /0.00334 = 248.0	0.92 /0.00339 = 271.0
2nd lightest to test card	0.0123/0.00317 = 3.88	0.0166 /0.00312 = 5.32	0.0193/0.00317 = 6.09
2nd lightest to reading page	0.0123/0.00348 = 3.53	0.0166 /0.00334 = 4.97	0.0193/0.00339 = 5.7
3rd lightest to test card	0.0101/0.00317 = 3.19	0.00137/0.00312 = 4.39	0.0156/0.00317 = 4.92
3rd lightest to reading page	0.0101/0.00348 = 2.90	0.00137/0.00334 = 4.1	0.0156/0.00339 = 4.6

ducibility of the results obtained and that the variations produced by the changes in lighting effects are much greater than the variations in the test itself, subject to all the variable factors which may influence it, the mean variation from the average result has been computed in each case. The value of this in per cent. is given in column 15.[8]

TABLE VIII.

Compiled from Table IV to show the mean variations in surface brightness for the six types of reflector used.

Division A.

Measurements considered	Mean variation for the three reflectors, Reflector type I	II	III	Percentage of mean variation for the three reflectors, Reflector type I	II	III
All	0.02885	0.0373	0.0405	134.8	148.0	148.4
All but the reflector	0.00667	0.00412	0.00411	93.2	75.3	70.3
All but the reflector and the spots above the reflector	0.000917	0.000884	0.0012	29.5	29.7	35.8

Division B.

Measurements considered	Mean variation for the three reflectors, Reflector type IV	V	VI	Percentage of mean variation for the three reflectors, Reflector type IV	V	VI
All	0.06494	0.08852	0.09597	168.0	170.8	170.5
All but the reflector	0.0020	0.00274	0.00342	42.4	56.0	62.0
All but the reflector and the spots above the reflector	0.00111	0.000964	0.00104	30.9	30.0	30.2

In Chart 1 a graphic representation is made of the results of this table. In constructing this chart, the total length of the test period is plotted along the abscissa, and the ratio of the time the test object is seen clear to the time it is seen blurred in the three-minute records before and after work is plotted along the ordinate. Each one of the large squares along the abscissa represents one hour of the test period, and along the ordinate an integer of the ratio.

So far in all our work we have shown for the sake of completeness of representation the gradation of surface brightness in three ways.—(1) Brightness measurements of prominent surfaces have been made. (2) Ratios have been given between surfaces of the first, second, third, etc., order of brilliancy and surfaces of the lowest order of brilliancy; and between sur-

TABLE IX.

Showing the tendency of the six types of reflector to cause loss of visual efficiency, or power to sustain clear seeing.

Reflector type	Watts	Volts	Intensity foot-candles			Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Total time clear ÷ total time blurred	Ratios reduced to common standard	Loss of efficiency expressed in percentage drop in ratio	Mean variation (per cent.)[9]
			Horizontal	Vertical	45°									
I	800	111.0	4.1	1.14	2.7	9 A.M.	80.2	62.2	138.5	41.5	3.34	3.5	—	—
						12 M.	80.0	62.2	133.0	47.0	2.83	2.97	15	0.86
II	800	110.0	3.7	1.13	2.6	9 A.M.	80.0	64.0	139.0	41.0	3.39	3.5	—	—
						12 M.	79.5	64.0	115.0	65.0	1.77	1.82	48	0.77
III	800	107.5	4.2	1.16	2.6	9 A.M.	80.0	64.0	145.0	35.0	4.14	3.5	—	—
						12 M.	79.5	64.0	118.0	62.0	1.9	1.60	54	0.70
IV	800	105.5	3.8	1.15	2.5	9 A.M.	79.5	63.6	145.0	35.0	4.14	3.5	—	—
						12 M.	79.0	63.6	112.0	68.0	1.65	1.39	60	2.0
V	800	105.5	3.7	1.15	2.6	9 A.M.	79.5	63.6	140.1	39.9	3.51	3.5	—	—
						12 M.	78.5	63.6	91.0	89.0	1.02	1.017	71	0.86
VI	800	107.5	4.2	1.16	2.7	9 A.M.	79.5	63.6	141.0	39.0	3.62	3.5	—	—
						12 M.	78.5	63.6	89.0	91.0	0.978	0.945	73	1.0

TABLE X

Showing a comparison of the tendency of the six types of reflector used to cause loss of efficiency and to produce ocular discomfort. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

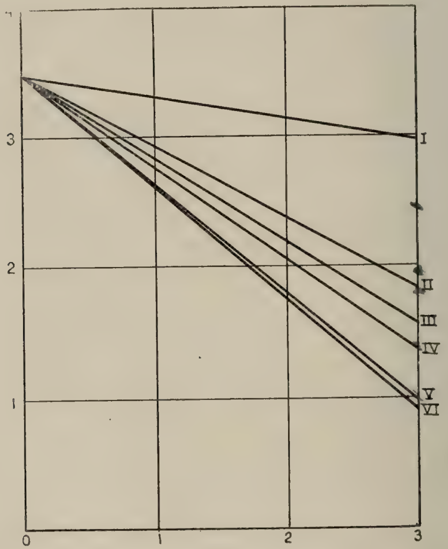
Reflectors	Volts	Foot-candles Hori-zontal	Foot-candles Vertical	Foot-candles 45°	Per cent. loss of efficiency	Mean variation (Per cent.)	Time limen of discomfort in seconds (not reading)	Mean variation (Per cent.)	Change produced by changing type of reflector (Per cent.)	Time limen of discomfort in seconds (reading)	Mean variation (Per cent.)	Change produced by changing type of reflector (Per cent.)
Type I . .	111	4.1	1.14	2.7	15	0.86	80	1.1		25	1.6	
Type II . .	110	3.7	1.13	2.6	48	0.77	45	1.5	43.8	17	1.5	32.0
Type III .	107.5	4.2	1.16	2.6	54	0.70	34	1.8	24.4	14	2.1	17.7
Type IV .	105.5	3.8	1.15	2.5	60	2.0	21	2.4	38.2	10	2.0	28.6
Type V . .	105.5	3.7	1.15	2.6	71	0.86	17	2.2	19.0	8	2.3	20.0
Type VI .	107.5	4.2	1.16	2.7	73	1.0	15	2.7	11.8	6.5	3.0	18.8

faces of the first, second and third order of brilliancy and the brightness at the point of work. And (3) the mean variation from the average and the percentage of mean variation have been shown. In the consideration of these specifications, a number of

CHART I.

Showing the tendency of the six types of reflectors to cause loss of visual efficiency, or power to sustain clear seeing. Ratio time clear to time blurred is plotted against length of test period.

		Foot-candles		
Reflector	Volts	Horizontal	Vertical	45°
Type I	111	4.1	1.14	2.7
Type II	110	3.7	1.13	2.6
Type III	107.5	4.2	1.16	2.6
Type IV	105.5	3.8	1.15	2.5
Type V	105.5	3.7	1.15	2.6
Type VI	107.5	4.2	1.16	2.7

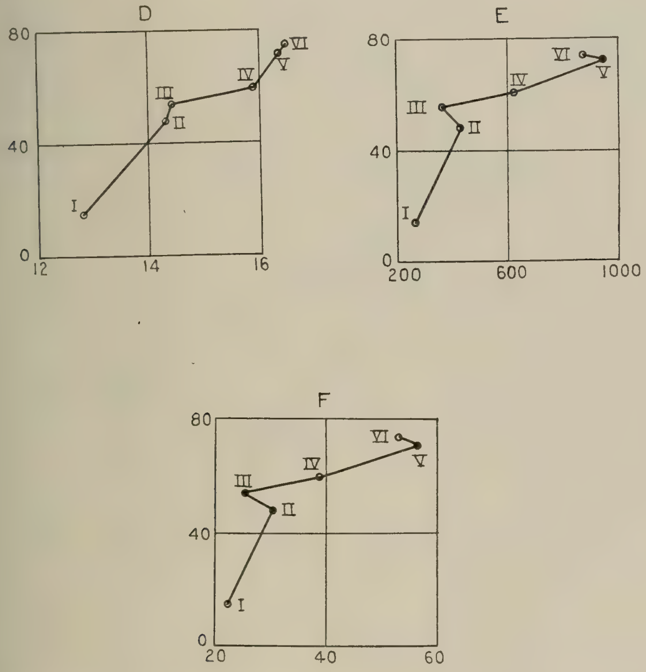


single items might be selected as of possible significance in relation to the effect on the eye. Among these may be mentioned the order of magnitude of the highest brilliancies; the average brilliancy; the ratio of the highest to the lowest order of brilliancy the ratio of the highest order of brilliancy to the average bril

along the abscissa represents one hour of the test period, and along the ordinate, 0.1 ratio, time seen clear to the total time of the observation. That is, in this method of treating the results, since the ratios, or the quantities to be plotted along the abscissa, are much smaller than they are in the former method, the scale

CHART IV.

Showing the tendency of the six types of reflector to cause loss of visual efficiency or power to sustain clear seeing. In curve D percentage drop in ratio time clear to time blurred is plotted against ratio of lightest surface to average brightness; in E, against ratio of lightest surface to darkest surface; and in F, against ratio of average brightness to darkest surface.



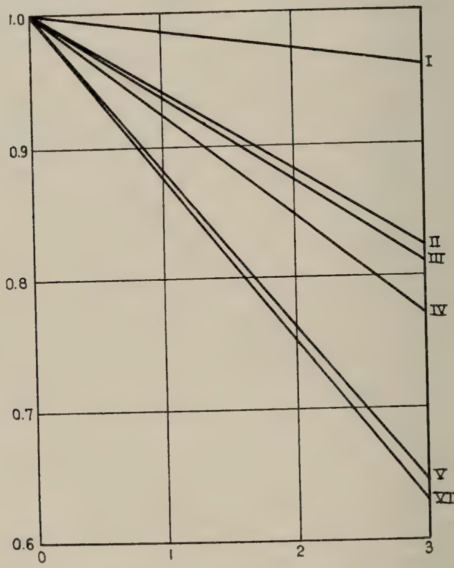
has been multiplied by 10 for convenience of representation. In order that the lines may all start at a common point, the initial ratios are reduced to 1 as a common standard. In Chart VI, per cent. loss of efficiency as evaluated by this method is plotted against intrinsic brilliancy of reflector. As before, intrinsic brilliancy of reflector is plotted along the abscissa, and per cent.

loss of efficiency along the ordinate. A comparison of these results with the former will show the same order of rating of the reflectors but a slight change in the position in the scale given to some of the reflectors. For the purpose of discovering what is

CHART V.

Showing the tendency of the six types of reflectors to cause loss of visual efficiency or power to sustain clear seeing. Ratio of time clear to total time of observation is plotted against length of test period.

		Foot-candles		
Reflector	Volts	Horizontal	Vertical	45°
Type I	111	4.1	1.14	2.7
Type II	110	3.7	1.13	2.6
Type III	107.5	4.2	1.16	2.6
Type IV	105.5	3.8	1.15	2.5
Type V	105.5	3.7	1.15	2.6
Type VI	107.5	4.2	1.16	2.7



the best way of treating the results of the tests, several method have been employed. Up to and including the present pape however, only three of them have been given in print: ratio c time clear to time blurred, ratio of time clear to total time c

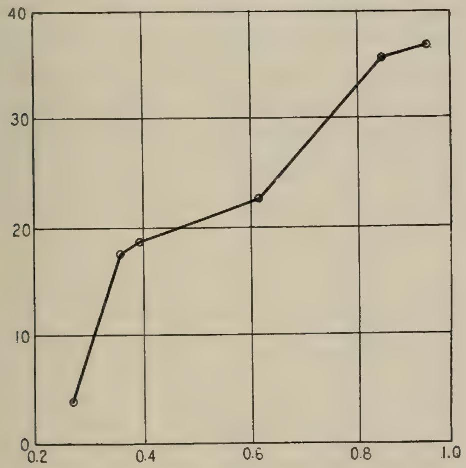
observation, and the per cent. of drop in the ratio time clear to time blurred. An ultimate decision with regard to what is the best method of treatment of the results can come, we believe, only with the consideration of a larger number of cases.

The work was concluded by determining for the six types of

CHART VI.

Showing the tendency of the six types of reflectors to cause loss of visual efficiency or power to sustain clear seeing. Percentage drop in ratio time clear to total time of observation is plotted against brightness of reflector in candlepower per square inch.

Reflector	Volts	Foot-candles Horizontal	Vertical	45°	Cp. per sq. in.
Type I	111	4.1	1.14	2.7	0.264
Type II	110	3.7	1.13	2.6	0.361
Type III	107.5	4.2	1.16	2.6	0.392
Type IV	105.5	3.8	1.15	2.5	0.614
Type V	105.5	3.7	1.15	2.6	0.848
Type VI	107.5	4.2	1.16	2.7	0.920



installations the relative tendencies to produce ocular discomfort. As before, two cases were made of this determination,—one when the eye was at rest, the other when it was at work. For a description of how the determination is made, and a discussion of the method that is used, see the TRANSACTIONS of the I. E .S., 1913, VIII, pp. 54-58; and 1915, X, pp. 496-501. Space will be taken here only for presentation of the results. These are given

in Table X. In this table are given also, for the sake of comparison, results expressing the tendency of the six types of reflectors to cause loss of ability to sustain clear seeing.

APPENDIX.

The reflectors used in this work were supplied by the Holophane Works of the General Electric Co., and are opal glass of light, medium, and heavy densities. They are all of the bowl type and of the same size, 8 in. Reflector I is a pressed Sudan toned brown; reflector II, a blown white glass, toned brown (experimental); reflector III, a pressed Sudan; reflector IV, a pressed Druid; reflector V, a blown Veluria; and reflector VI, a blown white glass (experimental). Reflectors I, III, IV and V are commercial products, but II and VI are special, inserted in the series to give gradations in density. As was stated in the text these reflectors presented considerable unevenness of surface brightness. This was especially true of the pressed reflectors which are smooth on the inside and grooved on the outside. The glass in these grooves being thinner than in the spaces between a very uneven surface brilliancy is given to the reflector. Further reflector IV, because of its imperfect diffusion, was quite a little brighter in the center, at the location of the filament, than at the top and bottom. In determining the brightness of these reflectors overlapping readings were taken and an average obtained.

NOTES.

[1] The truth of this should be obvious to any methodological critic. It is in fact the logical corollary of the application of a new test to a new field. Until a range of application is made which is reasonably representative of the work for which the test is designed to be used, a complete description of the test itself, including a statement of the factors which may influence its results and full direction how to use it, cannot possibly be given without more presumption than we care to exercise. While an attempt to do this might afford a certain amount of specious satisfaction to the practicing engineer, it would be superficial and incomplete and calculated to produce trouble in the work of others. When in the opinion of the authors a sufficient range of work has been covered, a separate paper will again be devoted to the test method itself in which data collected from all the work will be submitted and the adaptability and application of the method to different kinds of work will be discussed. It is clear, we think, to anyone who has had experience in developing and applying a new test that this can be done more safely and effectively at the close of a section of the work which is sufficiently comprehensive to be representative of the accomplishment of the test, than at its beginning or while the work is yet in progress. In this later paper data will be submitted also on four types of test devised by us to detect changes in the functional condition of the retina as the result of working under different conditions of lighting.

Two points keep coming up, however, with a degree of persistence which ma

justify a somewhat detailed discussion at this time. The first pertains to the sensitivity of the test to factors extraneous to the conditions that are being tested. The point was briefly discussed in the original paper on the test and again in the two succeeding papers. It was brought out more especially in Mr. Cravath's paper and in the discussions following it. Among other things it was shown in this paper that by purposely varying these factors in some extreme way they could be made to influence the results of the test. The more crucial point was not shown however; namely, that they operate against the usefulness of the test when the work is done under the conditions that ordinarily obtain in a well conducted experiment; nor does the paper contain any evidence that Mr. Cravath thinks this is the case. In our own work a different plan has been pursued with regard to this point. Instead of trying to find out what effects could be produced by means of procedures that would not be permitted in making a test, every care has been taken from the beginning to eliminate or hold as constant as possible all extraneous factors which might influence the general and muscular efficiency of the eye, and to check up the effectiveness of this control by carefully determining the mean variation in the results for each set of lighting conditions. This we have considered to be the most direct and feasible plan of conducting the work. In any event, it is obvious that there is no need of futile speculation concerning the possibilities of influence of these factors, nor of any indefiniteness either in the discussion or investigation of the point, so long as the actual value of the influence can be measured by determining the mean variation and its relative value be estimated by comparing the mean variation with the variations produced by changing the conditions to be tested. That is, a measure of the absolute and relative value of these factors is readily available and this measure has been carefully used at every step in the work. We need scarcely to point out that it is a well recognized principle of experimentation in comparative work such as we are doing that as long as the mean variation is safely within the experimental variation, the method is considered satisfactory for the purpose for which it is being used.

In this connection it may not be out of place to give here a more detailed account than has yet been given of the method that has been used in selecting and training observers. Care is exercised in the first place to choose one who has shown a satisfactory degree of precision in threshold and equality judgments in other optical work in the laboratory, and whose clinical record shows no uncorrected defects of consequence The observer is then practised on the three minute record under a lightin condition selected and maintained for the purpose, until a satisfactory degree of reproducibility is shown. These records are usually run in series of five with a twenty minute rest interval between each record. So far we have not published the results of an observer who has not been able to attain a reproducibility in the time seen clear of 1 per cent. for a series of five records in these preliminary experiments, although this degree of precision is unnecessary unless the observer is being trained for work in which there are very small differences in the conditions to be tested. Since these records are run with no change in the lighting conditions and with rest intervals to prevent general or optical fatigue, they serve primarily as a training in making the judgment and as a check on the precision of the judgment. In the second stage of preparation the observer makes a number of three hour tests with records before and after work for two or more lighting installations, and the mean variation of the results from the average is determined. Again, if a sufficiently small mean variation is not shown where there has been no change in the lighting conditions, the observer is not allowed to take part in the actual work of testing. This last mean variation is the final preliminary check upon all the factors that may vary under the control imposed,—lack of reproducibility in the judgment, variable physical and mental fatigue, etc. The final check is had in the course of the work itself. That is, a number of tests are made for each lighting condition of the series to be investigated, and the mean variation is determined for each and compared with the variations that are produced by the changes in the conditions to be tested, to find out to what extent these variations may be ascribed to the changes made and to what extent to the normal variation of the test. How much larger is the variation which is produced by changing the lighting conditions than is the normal variation for each condition may

be seen by comparing Columns 14 and 15 of Table IX. In the work of the preceding papers the excess of the experimental variation over the mean variation was much greater still as might be expected from the greater differences that were present in the lighting conditions tested. For example, in five three hour tests for the indirect system for Position I (see this TRANSACTIONS 1915, X, pp. 413-426) the mean variation in per cent. was 1.1; for the semi-indirect system it was 1.4; and for the direct system, 1.2; while the percentage drop in the ratio from beginning to close of work for these systems was respectively, 8.5, 72.3, and 80.9. Similar citations may be made for the other conditions tested. When one compares in these cases the mean variation with the magnitude of change of ratio produced by changing the lighting system, it becomes obvious how unnecessary has been the concern about the influence of extraneous factors in case of the work that has as yet been done. In fact, the mean variation has been so safely within the experimental variation that the writers have not felt it necessary heretofore to make the numerical comparison in print. It is so well recognized as an experimental principle that the experimental variation shall safely exceed the mean variation that it has been their custom to give the comparison only when there exists some grounds for doubt. Heretofore, we have, as a general case, been working with conditions that produced a large difference in results.

As bearing on another phase of the question of reproducibility, namely, where a long interval has elapsed between two series of tests, we may cite one example where two series were taken under the same lighting conditions a year apart, and the variation in the average per cent. loss of efficiency was only 0.3. In this case a favorable lighting system was used, the initial ratios were closely the same, and the control in general good, although no especial care was taken to make it so more than what is ordinarily exercised. It is not presented, however, as a typical instance. It happens to be the only case of which we have a record, where a long interval has elapsed between two tests.

Moreover, there is nothing in the nature of the test other than its superior sensitivity that should make it more susceptible to the influence of extraneous factors than any other test of acuity. The principle of the test will be remembered from the earlier papers. It is merely the conventional acuity test subjected to certain features of standardization for the sake of greater reproducibility, and made into an endurance test to give it additional sensitivity. The older test had not been found to be sufficiently sensitive to fatigue conditions to warrant adoption in our work. This test is in fact not meant to be a fatigue test. It was designed to test the dioptric condition of the eye, and may be used with more or less success as a test of how far a given lighting condition is conducive to clear seeing with *a maximum of momentary effort*; but it has not the essentials of a fatigue test nor of its converse, the ease with which clearness of seeing is attained,—which is what is needed primarily for the selection of lighting conditions for the greater part of the work that we are ordinarily called upon o do. Almost if not quite as good results, for example, may be gotten with it after work as before, when there is every other reason to believe the eye has suffered considerable depression in functional power. The reason for this is obvious. Although greatly fatigued, the eye can, under the spur of the test, be whipped up to give almost if not quite as good results as the non-fatigued organ when only a momentary effort is required. (See Column 8, Table IX, and former papers.) If fatigued, however, it can not be expected to sustain this extra effort for a period of time. The demonstration of this fact led early in our work to the introduction of the time element into the test. The principle involved is not a new one. It is merely the application of a very old and well known one to the work of testing for optical fatigue. If, for example, a sensitive test is wanted for the detection of fatigue in a muscle, as good results can not be expected if the test requires only a momentary effort on the part of the muscle as would be attained if the endurance of the muscle were taken into account. For our purpose, therefore, the old acuity test has been made into an endurance test, in which the fatigue or loss of functional efficiency of the eye is measured by its power to sustain clear seeing for a period of time. As such it should and does show a sensitivity for detecting fatigue far beyond what can be attained by the older and more established test when it is used

for that purpose. And being a test which is more sensitive to functional changes in the eye, it doubtless does show in some proportion to its greater sensitivity more effect of the indirect as well as of the direct factors that influence acuity; but since the indirect factors can be subjected to control, while the direct factors are varied, there is in proportion to the sensitivity of the test and the control exercised a gain for the purpose for which the test is used. That this gain is great is shown in all our work by a comparison of the size of the mean variation with that of the variation produced by the change in the conditions to be tested.

The second point we wish to discuss here refers to the part played in our experiments by a factor known among psychophysicists as the error of expectation. The belief that there is a need to take account of this error in sense judgments arises from the difficulty in keeping the observer in ignorance of the test material and of a certain amount of the experimental procedure. In our experiments there are just two points on which the observer has knowledge: namely, the test object and the lighting conditions or system under which the work is done. All the rest is kept concealed from him unless the experimenter should in turn serve as observer in which case his results are checked up by those of observers who have not served as experimenter. We will consider this factor first in relation to the test object. The observer knows what the test object is (the letters li in 8 point type) and is told to record, for example, when the dot is seen separate from the vertical line in the letter i. The question at issue then is whether proper account is taken in our experimental procedure of the influence of expectation on this judgment. The question can be discussed the most comprehensively perhaps by first considering rather broadly the status and development of experimental method with regard to this factor. As we have already intimated, the probable influence of expectation is an inherent difficulty in all sense judgments,—photometric, acuity, threshold, etc. That it can not be entirely eliminated is, we think, generally conceded as axiomatic. Psychophysicists have, therefore, turned their attention to attempts to compensate for it, and a need has been felt to do this in most cases only when the work requires that the determination be made with a great deal of precision. Different methods may be employed for this purpose all of which are more or less open to question. The one most frequently used perhaps, is the method of ascending and descending series. From a consideration of this method an idea may be had in a general way of all the methods of its class. Rather than to eliminate or even to lessen the operation of the factor, the purpose of this method is to control its direction and to plan the experiment in opposing series, so as to compensate for its influence in the final result. That is, in making a threshold determination, for example, the series in one case is begun below the threshold, and the observer is told that the stimulus will be increased until the threshold is reached; in the other case the procedure is reversed. For the final result an average is taken of the values so determined on the assumption that expectation in the two cases will influence the determination by equal amounts in opposite directions. Much has been said in the literature of psychophysics with regard to whether this method accomplishes what it is intended to accomplish, and more might be said; but it is immaterial for our purpose whether it does or not, for it is obvious that it could not be applied to our 3 minute records, for here the image to be judged rises to the threshold of discrimination independently of the control of either the observer or the experimenter. The individual judgments, therefore, could not be arranged in opposing series for the purpose of compensation. An entirely different type of method is to use an objective check on the judgment of the observer, and by this means endeavor to weed out from the results the influence of subjective factors. We tried for several months to devise a means of changing the stimulus in such a way that an objective check could be had on the registration of the observer without sacrificing the principle of the test. Such a change, however, could not be made in the test object which did not at the same time permit the eye to relax its strain at the instant of change, which it is obvious destroys the very feature which gives the test its superior sensitivity. The attempt to get an objective check, however, was made more for the sake of offsetting possible criticism than it was because of any belief that it was necessary for the purpose for which the test has so far been used;

for, as we have already stated, a determination of the mean variation for the 3 minute record, each one of which consists of a number of separate judgments, had shown us that the influence of expectation as a source of variable error is of negligible consequence. That is, the mean variation is the measure of the aggregate effect of all the variable factors including expectation, if indeed it be a source of error in the case under consideration, and it was found to be too small as compared with the variations produced by the changes in the conditions tested to be the cause for any concern for the purpose of the work. Moreover, it will be remembered that a knowledge of the test object is given to the observer as one of three changes that were made in the conventional acuity test to minimize very obvious sources of variable error, among which were memory and expectation, and to give a greater reproducibility to the judgment. We can do no better probably than quote from the original discussion. "Visual acuity tests of the Snellen type, especially when used in work in which it is required to make successive tests on the same person, are open to the following objections. (*a*) The judgment is in terms of recognition. A letter may be recognized when it is not seen clearly. In any judgment based on the recognition of even a single letter, memory plays an important role. It is, so far as the writer knows, impossible to standardize this memory factor and to obtain results strictly in terms of acuteness of vision. (*b*) The test card is made up of quite a long series of letters. As the test progresses the letters are memorized more and more completely. It is practically impossible to eliminate this progressive error when a number of successive judgments have to be made as is the case before a final result is reached in any single visual acuity test and as is especially the case when a number of successive tests have to be given to the same person, which happens in much of the work involved in the solution of the problem here proposed .... (*c*) The Snellen series contains quite a large number of letters. The eye is found to fatigue and vision to blur before the series is completed. This introduces an error which it is practically impossible to render constant." All of the above errors were eliminated, or at least minimized, in the tests finally adopted by us by changing the type of judgment and by adopting a simple test object, made up of only two characters, the letters li in 8 pt. type. In this test the observer's acuity of vision is determined by the distance at which he can just clearly distinguish the two test objects. In practise it has come to be a matter of distinguishing whether or not the dot is separated from the vertical line in the image of the letter i. The results are thus rendered directly in terms of acuity of vision and the progressive errors due to memory and expectation are minimized. In this regard the significance of the change in the type of judgment from recognition to the judgment of the separateness of two simple objects, *e. g.*, the dot and the line in the letter i, should not be overlooked. When the criterion is recognition and the task set for the observer is merely to identify the test object with its name or some memory of it from past experience, as is the case in the old form of the test, memory and expectation play their maximum role. Any extraneous clue or a partial discrimination of the object may in fact serve as a basis for all that is required in the judgment. When, however, the task set for the observer is a different one and he is required to judge the presence or absence of a space between the dot and line in the letter i, the role of these factors is reduced to a minimum, and the task is narrowed down to the judgment of a space threshold, one of the simplest and most reproducible types of sense judgment. In short then, a knowledge of the test object is given to the observer as a part of the modification of the conventional acuity test to minimize the effect of variable factors, among which memory and expectation play the chief role. And that it has accomplished its purpose is abundantly attested by a comparison of the size of the mean variation given by the test so revised as compared with that given by the older form. We may add that the letter l is used in connection with the letter i for two reasons. (1) A steadier fixation is given than can be attained by so small an object as the letter i; and (2) a standard is afforded (an unbroken vertical line) in terms of which to judge the separateness of the dot from the vertical line in the letter i.

The only other way in which expectation can come into the experiment through knowledge on the part of the observer is, as we have already stated, through an

awareness of the conditions or lighting system tested. The observer can not work for three hours under a given lighting installation without being more or less aware that the same installation is being used as was used before, or a different one. Moreover, we do not see how this unfortunate factor can be completely eliminated unless imbeciles be used for observers. We wish to point out, however, that there is no greater liability to harmful influences from this factor in our test than in the older acuity test or any other that could be applied to the same type of work. We grant that, in any test that could be used, if observers of strong commercial or other bias should in two isolated trials get better results for one type of lighting than another, there might be grounds for suspecting that prejudiced observations were made: but if each condition were tested a number of times, as has been the case in all of our work, and a small mean variation were obtained for each series of tests, the result would look much more like the response of an organism to a constant set of conditions in obedience to physiological law than it would like a voluntary reproduction guided by prejudice, however strong and constant that prejudice might be. Here again the size of the mean variation is the check upon the validity of the results, for it is obvious, we think, even to a novice, that records taken at intervals of from one to five days could not show a close reproduction if the fidelity of the registration were in any way interfered with by the wishes or prejudice of the observer. Furthermore, it is only fair to say that it would be difficult to find a group of observers freer from a direct interest in lighting conditions or a knowledge of their significance than is the group from which the greater number of our observers are selected.

[2] These factors are the evenness of illumination, the evenness of surface brightness, the diffuseness of light, the angle at which the light falls on the work, intensity, and quality.

[3] The problem of installing is probably not the same for the inverted translucent as for the inverted opaque reflectors. In the latter case the height should be so adjusted as to give as nearly as possible an even distribution of surface brightness on the ceiling, and evenness of illumination on the working plane. In case the inverted translucent reflectors, however, if the distance from the ceiling is made great enough in all cases to produce these effects, it may throw the bright reflectors too low in the field of vision for the highest efficiency and the greatest comfort to the eye. In this regard the opaque reflectors have the advantage that it is always easier with them to get the brightest surface in the room out of the zone of most harmful influence in the field of vision. In later work we expect to conduct a series of experiments with the above reflectors in which the height from the ceiling is the factor varied.

[4] The track along which the test card was moved was parallel to the east and west walls of the room. When taking the test the observer faced the north wall in such a position that when the eyes were in the primary position the lines of regard were parallel with the east and west walls of the room, and approximately normal to the north and south walls. That is, the head was erect and held in such a position that the objects in the room, reflectors, etc., fell as symmetrically as was possible within the field of view. During the three hours of reading which intervened between the two three minute records, the observer moved just far enough back from the upright supporting the mouth board to give room for the book to be held, and to permit of a comfortable reading position. Care was taken to have the eyes sustain as nearly as was possible the same general relations to the objects of the room as were sustained when the three minute records were taken. This could be done either by holding the head erect, etc., or by tilting slightly backward in the swivel chair used by the observer and allowing the head to relax a compensating amount. So far as the direct optical effects are concerned, it would seem to be immaterial which of these positions is chosen, so long as approximately the same field of vision is obtained. The latter is usually preferred by the observer as causing less general fatigue. When taking this position, the book is elevated and held at ap-

proximately an angle of 45° (a little nearer to the vertical than this perhaps). The brightness measurements of the book at this angle and in the horizontal are not taken, however, so much because of this as to give the brightness of the book in two fixed representative positions at the point of work. Care is taken to have print of uniform size and distinctness for use with the three systems and to have a page which gives a comparatively small amount of specular reflection. Uniformity in these regards can usually be secured by using numbers of the same journal.

[5] It should not be needful to mention that the recording apparatus is screened from the observer's view while the test is being made. Before photographing, the screen was removed and the apparatus regrouped.

[6] This is the test station shown in Fig. 1, and of the four used in the former work is the one nearest to the south wall of the room.

[7] As has been stated in our former papers, in the consideration of the effect of a given lighting situation on the ability of the eye to hold its efficiency for a period of work, the age of the observer and the condition of his eyes should be taken into account. All of the observers who have been employed by us in this work have been under 28 years of age. Following is the clinic report of the eyes of the observer whose results are given in Tables IX and X, made by Dr. Wm. Campbell Posey of Philadelphia.

Observer R.

With glasses.—Vision of right eye = 20/25. Far muscle test = 0 ½ esophoria.
Vision of left eye = 20/20. Near muscle test = orthophoria.
Ophthalmoscopic examination.—Right eye = mixed astigmatism, ½ diopter.
Left eye = hyperopic astigmatism, 1½ diopters.
External condition.—Adduction good; eyes slightly divergent under cover; cornea clear; pupils, 2½ mm.; irides respond equally and freely to light, accommodation, and convergence stimuli.
Glasses worn during test.—Right eye = —S., 0.50 D.; —C., 0.37D., x 160°
Left eye = —C., 0.50 D., x 180°

Early in our work the problem arose whether the three minute records before and after work should be taken in the same room in which the work was done or in a separate room reserved solely for that purpose. To test this point, work was done in both ways. It was found that the effects of smaller differences in lighting conditions could be detected when both the three minute records and the work were done under the lighting conditions to be tested. That is, the total test procedure which includes both the three minute records and the reading, is more sensitive when it is all done under the conditions to be tested, than when a part of it is done under these conditions and a part in a separate room. Since the method is more sensitive when the whole procedure is conducted under the lighting conditions to be tested, we can see no reason why even the purist should demand that a part of it be done under the conditions to be tested and a part somewhere else, so long as the results are recognized to be the consequence both of the three minute records and of the reading. Our purpose, it will be remembered, has been to get a sensitive means of detecting the relative tendencies of different lighting conditions to cause a loss in the power of the eye to sustain its ability to see clearly; and the method is more sensitive when the three minute records, also, are made under the conditions to be tested. This, we may say, is our chief reason for the practice. A justification, we believe, is not logically needed. Moreover, the method so conducted is just as amenable to control and to checks upon its reproducibility, as if it were used in the less sensitive form. It is, in fact, considerably more amenable to control, for if separate room were used for the three minute records, very great care would have to be exercised to see that it was always illuminated with exactly the same intensity of light that was used in the room in which the reading was done. If the illumination were not accurately the same, a period of adaptation would have to be allowed before the three minute record could be made, which, in case of the record taken after work, would give the eye opportunity to recover from the fatigue induced b

the work. It is obvious that a great deal of difficulty would be encountered in accurately maintaining this control; and, if it were not so maintained, an error of considerable consequence would be introduced into the work. In getting control not only the illumination of the test object must be taken into account, but the brightness of the whole field of vision with its complex distribution of light and shade, for this conditions the state of adaptation of the paracentral and peripheral portions of the retina which in turn exerts an influence on the part of the retina that receives the image of the test object. It may be added also that adaptation effects in the paracentral and peripheral portions of the retina are stronger and more rapid than in the central portions.

In connection with the fact that the three minute records add sensitivity to the method when they are also taken under the conditions to be tested, we may say that we are now working on a short method in which three minute records with proper rest intervals are used. This test is rougher and less sensitive than the longer method, but if it can be made satisfactory, it might be more adaptable to practical work.

[8] It will be noted in this table that there is very little variation in the value of the initial ratios. We noted in each of our preceding papers and again in our discussion of Mr. Cravath's paper that the sensitivity of the test varies with the ratio of the working distance of the test object from the observer to the acuity distance. After considerable investigation of the point, we adopted, as a standard to be attained approximately, a ratio of distances that would give for the initial record a ratio of time clear to time blurred of 3.5. As might be expected, it is impossible to get this ratio of 3.5 exactly from any single ratio of working distance to acuity distance that can be determined in advance of the actual record. But with care a close approximation may be attained, and since the loss of efficiency is judged from the amount this ratio is changed from the beginning to the close of work, and not from the ratio itself, the failure to obtain it does not affect a comparison of the favorableness of different lighting conditions for the eye, any more than is represented by its effect on the sensitivity of the test. In short, the variations in this ratio from test to test form merely one of the group of variable factors, the check upon the effect of which on the results of the test, is the size of the mean variation; and, so long as this mean variation is safely within the amount of variation produced by changing the conditions to be tested, the control may be considered as satisfactory for the purpose of the work that is being done. That is, when this check is properly exercised, the influence of a variation in this ratio can not possibly be mistaken for the effect of the condition which is being tested. However, in the course of the determination of what value of initial ratio should be used, considerable study was made of the effect of varying the ratio. While space will not permit us to quote largely from these results here, still an idea may be given in the space at our command, of the order of magnitude of the effect that is produced. That is, we will take three cases including a range of differences amply great to cover what is ever apt to occur in actual work. In the first, the initial ratios were 2. and 3. (difference, 1); in the second, 2.67 and 5 (difference, 2.33); and in the third, 1.93 and 7.57 (difference, 5.64). The difference in the percentage loss of efficiency for the first case was 1.4; in the second, 2; and in the third, 1.7. The effect shown in these cases, it will be observed, is about of the same order as the normal mean variation of the test.

[9] In order to make a fair comparison between the drop in ratio time clear to time blurred caused by working under a given lighting condition and the mean variation of the drop, the percentage drop and the percentage mean variation are both estimated in the above table, also in the citation made in Note 8, p. 1129, on the same base, 3.5. If this comparison had not been wanted especially to show that the mean variation produced by changing the type of reflector, it would have been more in accord with custom perhaps to have expressed the mean variation as a percent. of the mean value of the drop. Computed in this way the value of the mean variation for Reflectors I-VI would have been in order 5.6 per cent., 1.6 per cent., 1.3 per cent., 3.3 per cent., 1.2 per cent., 1.4 per cent.; and for the citation in Note 8, they

would have been for the indirect system 4.5 per cent., for the semi-indirect system 0.7 per cent., and for the direct system 0.5 per cent. This method of estimating the mean variation gives, it will be noted, the largest per cent. variation for the most favorable lighting condition because the drop in ratio, the base on which the percentage is estimated, is the smallest for this condition. The actual variation we have found as a rule is, as might be expected, the least for the most favorable condition.

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DISCUSSION.

Mr. J. R. Cravath: Dr. Ferree calls his test a test "loss of efficiency of the eye." I think the term "eye-fatigue" is much briefer and more expressive. The work reported in a previous paper of Dr. Ferree covered conditions rather widely varied. The paper we have before us now covers conditions which come within fairly narrow limits of visible source brightness. The results have been especially interesting to me as a member of the Committee on Glare because we have, during the past year, attempted to formulate or to express certain limits of good practise which are least conducive to glare. In ordinary interior illumination, we state in our report, which is soon to be published, that contrasts of brightness of adjacent surfaces (I mean by adjacent surfaces, those which are adjacent within the visual field) should not be over a ratio of one to two hundred, and preferably not over one to one hundred. That ratio was taken as the result of an examination of a good deal of data, some of

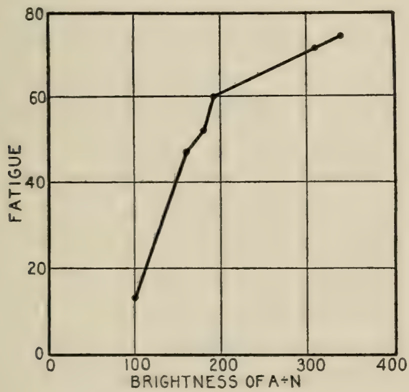

Fig. 1.

them in previous papers of Dr. Ferree. It was therefore of considerable interest to me to see how the results in the present paper

conform with these limits and in order to do that, I have taken the ratio between the brightest spot, which of course, is the reflector, and the point N on the room photograph a little to the right of the reflector, and plotted a curve, Fig. 1, corresponding to Chart II but, instead of using the brightness of the reflector, I have used the ratio of the brightness of the reflector to the darkest point along side of it; that is the point N. The ratios of A to N under 200 seem to give notably less fatigue than those above 1 to 200, which would confirm the judgment of our committee as well as the previous results obtained from various sources.

Dr. J. W. Schereschewsky: I want to congratulate Dr. Ferree on the extreme care which is evident in all these series of tests to obtain small mean deviations and secure reproducibility of results. I wish to call attention, however, to one factor, which in all probability, will have considerable effect on all tests which involve muscular action and that is the question of weather conditions. It is plain to all who have read this paper that tests of this kind such as Dr. Ferree has here published are labors requiring a great deal of care in arranging and carrying out, and it seems to me that we ought, by all means, in working tests of this character, to insure, as much as possible that the work shall not be thrown away because of great variations in the results due to extraneous factors. Now it seems to me that tests of this kind ought never to be conducted in very hot weather. The effect of high degrees of heat and humidity is to reduce the endurance of muscle. That seems to be plain from Prof. F. Lee's experiments which were done in the investigations of the New York Ventilation Commission, in which it was found that sections of muscles removed from animals which had been subjected to high degrees of temperature and humidity furnished on the average 40 to 50 per cent. less contractions than muscles of animals which had not been so exposed. Therefore, it seems to me that persons who conduct tests of this kind in very hot weather would find a great loss of efficiency of the eye simply from exposure to weather conditions; so in the future, when we are endeavoring to corroborate the results of these tests by similar tests, we must take the precaution never to undertake such tests except when the atmospheric conditions are distinctly comfortable.

Mr. T. W. Rolph: The data given in this paper are very valuable to us who have lighting systems to design.

I should like to call attention to the ratio between the brilliancy of the ceiling and brilliancy of the reflectors as obtained in these measurements. Reflectors 4 and 5 are typical reflectors of the class which is most commonly used to-day for semi-indirect lighting, and in this particular installation, which does not represent all installations, but is possibly a typical installation, the ratio between the brilliancy of the reflector and the brilliancy of the ceiling is one to fifty, and with reflector 5, one to sixty-one, taking the brightest point on the ceiling. Those are the reflectors which show the greatest eye fatigue, and this shows us how far we will still have to go in reducing intrinsic brilliancy in order to get semi-indirect lighting systems which are correct from the engineering standpoint. Now, reflector No. 3 is a commercial reflector which is being used to a certain extent for semi-indirect lighting. It is denser glass and it is harder to sell than reflectors 4 and 5, so that we who are working for better lighting in the commercial field have that to contend with. Reflector 3 shows a ratio between the brilliancy of the ceiling and the brilliancy of the reflector of one to sixteen. The densest reflector tested has a ratio of one to nine. Three years ago, in a paper on the "Engineering Principles of Semi-Indirect Lighting," I argued that, from the engineering standpoint, the brilliancy of the reflector in an installation should be approximately the same as the brilliancy of the ceiling. That was not particularly from the standpoint of eye protection, but from the standpoint of obtaining the maximum diffusion of illumination, arguing that if we are going to sacrifice the efficiency of direct lighting by installing semi-indirect systems, we should try to get the maximum engineering value of the semi-indirect systems, by obtaining maximum diffusion, and that this would be obtained when the brilliancy of the bowl is approximately the same as the brilliancy of the ceiling. This paper indicates that to obtain good eye-protection in semi-indirect lighting, we should work to very much denser glassware or very much lower brilliancy of reflector bowl than is generally practised to-day. Even a ratio of one to nine, where the reflector is nine times as bright as the ceiling, shows a considerable degree of eye fatigue.

There is one point I should like to bring out in connection with the measurement of the intrinsic brilliancy of these reflectors, and that is merely a suggestion that possibly a good way to obtain the intrinsic brilliance of a reflector of this character would be to take the candlepower as determined on the photometer, and the area of the reflector as determined on a drawing board, and thus find the candlepower per square inch, rather than to take luminosity measurements of the reflector at various points and average them. I believe it would be more accurate to take the candlepower of the reflector and simply divide it by the projected area in the direction of view.

Mr. J. R. Cravath: This question of what shall be taken as the criterion of brightness is something that Dr. Ferree evidently is not sure of, and I don't think any of the rest of us are—I mean, what particular contrast shall be taken. Mr. Rolph has just mentioned the contrast of the brightness of the reflector with the brightness of the ceiling above. Dr. Ferree has given us results showing the highest brilliancy, that is, the brilliancy of the reflector, and the average brilliancy, and the ratio of the highest to the lowest and the ratio of the highest to the average, the ratio of the average to the lowest and the ratio of the highest to the brilliancy of the point of work. There is such a great deal to be said in favor of his objection that, possibly, in a case where the subject is working continuously on desk work or reading that the ratio of the brightest object in view to the work, that is, to the paper on which the eye is working, should be the criterion; because in that case, the brightest objects in view appear simply on the edge of the retina most of the time, while the paper is on the center; but for most practical purposes, I think perhaps the criterion adopted by the Committee on Glare of the ratio between the nearest adjacent surfaces would answer all practical purposes for the present. I also want to express the debt that I feel the practical men of the society owe to the investigators who bring out this kind of data; it is exactly what we need to make progress in our work.

Dr. C. E. Ferree (In reply): I suggested in a former paper that, theoretically considered, better results should be gotten with the semi-indirect reflector of such a density as to give a surface brilliancy equal to that of the ceiling spot than are obtained with

the totally indirect reflector. That is, if the reflector is made of the same brightness as the ceiling spot, the same light flux can be obtained with a lower intrinsic brilliancy of the brightest surface than if the light all comes from the ceiling spot because of the increase of luminous area. This is in agreement, I believe, with the general tenor of Mr. Rolph's discussion. Unfortunately, however, I have not yet been able to obtain reflectors of sufficient density to test the point directly. However, in the work that we have done, an increase in the density of the reflector, so far as we have been able to carry the increase with the reflectors supplied us for the purpose, has been accompanied by a consistent improvement in the effect on the eye. There is one thing to be claimed, however, in favor of the indirect reflector when all is said and done. It is easier with it to remove the brightest spot in the field of vision from the zone of harmful influence to the eye, especially in rooms of the height ordinarily found in dwelling houses, because with this type of reflector the brightest spot is always on the ceiling. With reference to the effect of position or rather height of the brightest spot in the field of vision, it may not be out of place to anticipate here in slight measure the content of a future paper. In the work of the present paper the reflectors were installed 30 inches from the ceiling. This is in accord with general practise for the installation of totally indirect reflectors in rooms of the height of our test room and is considered to give a favorable distribution of light and shade on the ceiling and a comparatively even distribution of light on the working plane. So installed, however, the brightest spot (the reflector) is dropped well into the field of view, especially at the outlets most removed from the observer. The question arises, therefore, whether semi-indirect reflectors should be installed according to the principles of indirect lighting, direct lighting, or whether some compromise should be made between the two. We have begun, therefore, a series of tests in which the distance of the reflector from the ceiling is varied. So far we have been able to finish the comparison for the reflectors of least and greatest density at distances of 30 in. and 15 in. from the ceiling. The 15-in. distance gave quite considerable improvement in the effect on the eye for the reflector of least density, but not nearly so much for the reflector of greatest density. This result suggests that a more careful

study should be made of the method of installing semi-indirect reflectors differing in density. It would seem that the denser they are the more nearly they can afford to be installed as indirect reflectors and the less dense they are the more nearly they should be installed as direct reflectors so far as eye effects of the kind revealed by our tests are concerned.

I have no doubt that Dr. Schereschewsky is right about the probable effect of excessive temperature on the results of tests such as ours. I am very frank to confess, however, that I never do anything on a hot day if I can help it; and I certainly would not conduct a test when the temperature is excessively high. Through the greater part of the year the temperature of our test room is kept within a small variation by thermostat control. If it is necessary to work on warm days electric fans are used; but on no account are tests ever made on hot, humid days. In fact nearly as much care has been taken, I should say, to secure uniformity in temperature control in our work as has been taken to secure a uniform control of illumination and brightness effects. I am confident, therefore, that our results so far have not suffered from temperature as a variable factor. If I may digress here for a moment, I should like to say, with no reference whatever to Dr. Schereschewsky, whose discussions I have always found to be most considerate and intelligently liberal in tone, that I am becoming somewhat tired of the subject of extraneous factors. To speculate about their probable influence may be of considerable cultural value to those who have heretofore thought little about the subject, but there is no need to worry about their influence or to stand in the way of reasonable progress when a gauge on the amount of their influence may be and has been had at every step in the work. In this latter connection I refer to a careful determination of the mean or average variation. If this is done as it has been done at every step in the training of the observer; if moreover it is done for each condition tested and a comparison made of its amount with the amount of variation produced by changing the condition tested; exact knowledge is had in every case whether or not the results obtained are significant. The subject of gauging the influence of variable factors is too old and has been too carefully worked out to justify the raising in any

scientific body of as much elementary discussion as has been raised with regard to it in this Society. The procedure in general is very simple and straightforward. Train the observer on every feature of the test method with careful attention to the size of the mean variation. In the actual work determine the mean variation for each set of conditions tested and compare it with the variation produced by changing the conditions to be tested. If its sum for any two sets of conditions is not less than the difference between the average results obtained for the two conditions these results, it is usually considered, can not be claimed as significant. I have spent months, for example, in the training of an observer on the different features of the test method, only to discard him at the end of that time because a sufficient degree of precision of record could not be obtained under a constant set of lighting conditions. Those who have shown in such a course of training an unsatisfactory degree of precision usually reveal on examination, I may say, some uncorrected optical defect. Muscle imbalance more often than any other seems to have been the defect in the cases which have so far given us trouble. This may mean that the extrinsic more often than the intrinsic muscles are the cause of a variable performance on the part of the eye in tasks such as we have set for it in our tests, but it is also probable that the occurrence is due to a considerable extent to the fact that in ophthalmological practise small defects in muscle balance are more often left uncorrected than are, for example, refraction defects.

In concluding my comments on this point I think I may be justified in mentioning that I have spent a greater number of years than I like to recall in trying to get control of the variable factors that influence the response of the eye; and that I have added considerably to the precision of its performance under experimental conditions, I can only call upon my published work to testify. It is not likely, therefore, that in the course of developing a new test I would show such a degree of incaution with regard to the most elementary and well-known principles of experimentation as was made the subject of serious and somewhat pretentious inquiry in the discussions of the paper preceding the present one, and in the discussions aroused by Mr. Cravath's paper.

I am glad Mr. Cravath has given us still another way of plotting the results of the tests against brightness effects. It has not occurred to me, however, to attach any especial importance as a separate factor to the ratio of the brilliancy of the brightest area to that of its immediately contiguous surroundings. There are, for example, only two possible effects that I could conceive to be due to this relation, neither one of which would seem to me to warrant making of it a separate factor. (1) It would enhance by physiological induction in some proportion to the difference in physical brightness, the brightness of the sensation aroused by the reflector and thus increase its power to set up muscular strain by distracting the eye from the adjustment needed for the work in hand. So considered, however, its action would merely be that of an auxiliary factor, supplementary to the actual brightness of the reflector. As such it is of course of a great deal of importance, greater perhaps, for example, that the relation of lightest to darkest surface, as brightnesses are graded in a room ordinarily well illuminated. In short it would seem to me that the point of reference in determining the relations that are of importance to the eye is the brightness at the point of work. Any extreme deviation above or below this brightness, especially above, or anything that would make these deviations conspicuous to vision would seem to me to be of prime importance. I would, therefore, consider it an important addition to our present method of specifying brightness effects to give more detailed measurements, so far as is practicable, of the surroundings immediately contiguous to the brightest spot, because the effect of that spot upon sensation is to an important degree dependent upon the immediate surroundings; but I would by no means be willing to make these measurements and that of the brightest spot the sole specification of brightness effects, as Mr. Cravath suggests might be sufficient for our present needs. Moreover, it must not be overlooked in this connection that a curve plotted on a basis of the ratio of A, brightness of the reflector, to N for the different conditions tested must give a curve very similar to that plotted on the basis of the brightness of the reflectors alone, for N does not vary greatly from a constant value for the six sets of reflectors we have used. Obviously, therefore, cognizance should be taken of this fact before too much general importance is attri-

buted to this ratio as a separate factor from the shape of the curve plotted by Mr. Cravath for this particular set of conditions. (2) There might, it is conceivable, be some unknown effect on the retina which directly depresses its functional power or indirectly disturbs the adjustment of the eye. I have, however, already tested quite extensively the tendency of different lighting conditions to depress the functional power of the retina for as much as ten hours of continuous work and have found reason to believe that very little indeed of our results for the tests for loss of efficiency could be ascribed to a depression of retinal function. There are four ways, I may say, in which a change in the functional activity of the retina may be manifested: (a) a change in sensitivity to color and brightness; (b) a change in lag or the time required for the sensation to reach its maximum; (c) a change in the susceptibility to fatigue or exhaustion, measured by rate of exhaustion; and (d) a change in the power of recovery, measured by rate of recovery. All of these points were covered in the tests mentioned above. Short of such an investigation a complete record can not be given of the functional state of the retina at any time or as the result of any condition or set of conditions to which it may be subjected. But when such tests have been conducted for a period of exposure of the eye to the conditions tested more than three times as long as was used in the tests for loss of efficiency, it would seem reasonable to conclude that the results of this latter test could not be ascribed to any considerable extent to a depression of retinal activity.

Mr. Cravath has always quarreled with me over what the test should be called and perhaps on good grounds. If "fatigue" is a more palatable term to the engineer than "loss of efficiency," I am quite willing that the test shall be called a fatigue test. I have in fact called it that part of the time myself. My reason for calling it something else in the beginning was primarily one of profession. Among men in physiological and psychological optics the term fatigue as applied to the eye has been, since the days of Fechner and Helmholtz, a technical term connotating a retinal condition. It was chiefly to avoid the chance of confusion with the narrower usage of fatigue that I chose the broader term loss of efficiency as a brief designation of what is really tested, namely, the loss in the power of the eye to sustain clear seeing.

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A NEW METHOD OF HETEROCHROMATIC PHOTOMETRY

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In a former paper[1] it was stated that a satisfactory method of photometry should combine the following features. (1) It should enable us to detect small differences in luminosity and to reproduce our results for a given observer with a small mean variation and for a number of observers with a comparatively small mean variation. That is, the method should possess an adequate degree of sensitivity, and should give results with a satisfactory degree of reproducibility.[2] (2) It should be known either to possess of itself logical sureness of principle or its results must agree in the average with those of some method which can be shown to possess this sureness of principle. Methods having these features have been developed for the photometry of colorless light. The problem for the photometry of colored light, however, has presented great difficulty.

The methods for the photometry of colored light may be grouped under two headings: the direct and the indirect methods. In the former class we have the method of direct

[1] Ferree, C. E. and Rand, Gertrude, 'A Preliminary Study of the Deficiencies of the Method of Flicker for the Photometry of Lights of Different Color,' *Psychol. Rev.*, 1915, 22, pp. 110–162.

[2] It is scarcely needful to point out in this connection that the method should give results with a satisfactory degree of reproducibility for observations separated both by short and by long intervals of time.

comparison or as it is sometimes called the equality of brightness method. This method is generally accredited with sureness of principle but it is deficient on the side of sensitivity and reproducibility when lights differing in color value are compared.[1] Of the latter class the method of flicker has received the greatest amount of attention and has been the most favored. But in our former paper it was shown (1) that the method of flicker, so far as it has been developed up to the present time, does not possess of itself the sureness of principle needed to meet the requirements of a satisfactory method; and (2) that as yet its results have not been found to agree on the average with those of any method which can be shown to have this sureness of principle. It was also stated that in a later paper a method of photometry would be described which possesses approximately as high a degree of sensitivity and of reproducibility as the method of flicker and gives results which agree very closely on the average with those obtained by the equality of brightness method, much more closely than results obtained by the method of flicker. It will be the purpose of this paper to give a brief description of this method. It was first used by the writers in connection with work in color sensitivity for the purpose of detecting small changes on the illumination of a room by daylight.[2] Although not so convenient perhaps as the equality of brightness method for many of the purposes for which photometry may be used, for this work the method did not present any great amount of difficulty, and it proved to be much more sensitive than the equality of brightness method. The equality of brightness photometers of the Sharp-Millar type, for example, are very insensitive for the determination of the illumination of a room by daylight, because the standard field

[1] *Loc. cit.*, pp. 114–115.

[2] See Ferree, C. E. and Rand, G., 'An Optics-Room and a Method of Standardizing Its Illumination,' *Psychol. Rev.*, 1912, 19, pp. 364–373; Rand, G., 'The Effect of Change in the General Illumination of the Retina upon Its Sensitivity to Color,' *ibid.*, pp 463–490; 'The Factors that Influence the Sensitivity of the Retina to Color: A Quantitative Study and Methods of Standardizing,' *Psychol. Rev. Monog.*, 1913, 15, No. 62 pp. 79–166; see also Ferree, C. E., 'Tests for the Efficiency of the Eye Under Different Systems of Illumination and a Preliminary Study of the Causes of Discomfort,' *Trans Ill. Eng. Soc.*, 1913, 8, p. 51.

illuminated by the tungsten lamp is deep orange in color, while the comparison field illuminated by daylight is clear white. This difference in color tone makes the judgment of equality of brightness difficult to make, and renders the instrument extremely insensitive for daylight work.

So far as the type of judgment is concerned, the method we are about to describe is in reality an equality of brightness method but it has the important advantage that the observer is never required to judge impressions differing in color quality. In making a photometric balance by this method, the feature is thus eliminated which has from the beginning of the work of measuring light intensities rendered the equality of brightness method difficult of application to heterochromatic photometry. Because of this factor we have at the suggestion of certain photometrists undertaken to work out the principle on which the method is based in a way that will be of general service to the work in heterochromatic photometry and to secure data on the points in terms of which a verdict is rendered for every method of photometry, namely, the sensitivity and precision of the method, and the agreement of its results with those obtained by the equality of brightness method.

The method is based upon the extreme sensitivity of the peripheral retina to brightness contrast, especially to the induction of black by a white screen. Not only is the peripheral retina extremely sensitive to brightness contrast, but, which is the crucial point of the method, very small changes in the illumination of the contrast screen produce a change in the amount of the contrast. That is, for any part of the retina, for example, the amount of contrast induced by the surrounding field upon a contrast stimulus increases with decrease of illumination. In the peripheral retina we have an extreme case of this. In this part of the retina very small changes of illumination indeed are required to produce a noticeable change in the amount of contrast induced, especially when the surrounding field is white and the stimulus is a gray of the proper brightness.

The apparatus needed for the method consists of a vertical

screen 60 × 50 cm. with an opening 15 mm. in diameter midway between top and bottom and 16 cm. from one edge, a motor to carry the measuring discs, and a photometer bar. The surface of the screen is covered with Hering mat white paper, or preferably with a paper overlaid with magnesium oxide deposited from the burning metal. This screen is graduated in the horizontal meridian from the center of the 15 mm. opening. Over the opening between the white covering and the screen is placed the gray which is to serve as the contrast-stimulus. Nos. 3–5 of the Hering series of standard gray papers were found to serve this purpose best for the intensities of light we used in the work the results of which are given in Table I. The measuring discs were made up of a sector of the same gray as was used for the contrast-stimulus and a sector of black, the varying proportions of which produce the match which is needed between the stimulus gray darkened by contrast and the measuring disc. The measuring disc was carried by a motor the shank of which is at one end of the screen and normal to it. When in position, the inner edge of the disc extends approximately to the 20° point of the graduations, and is about 3 cm. in front of the screen.[1] Immediately in front of the disc and 25° from the center of the stimulus-opening to the temporal side is placed the fixation-point.[2] The photometer bar was placed in a

[1] The measuring disc was placed this distance in front of the screen partly to give freedom of rotation but primarily to eliminate any induction by the screen on the disc. That induction is not present in any considerable amount under the conditions described above, is evident from the following considerations. (*a*) It is not directly detectable by the eye; and (*b*) a very high sensitivity is attainable by the method which could not be the case were induction present to any degree, for if it occurred in amounts great enough to influence sensation, the effect would obviously be to lower the sensitivity of the method. That there has been no lowering of sensitivity from this cause is rendered probable by the fact that approximately as small differences can be detected for lights differing in color quality as can be detected by Lummer-Brodhun photometers of the most improved type when the lights compared are of the same color quality.

[2] Care should be taken not to place the fixation-point so far from the stimulus-opening that the color used is seen of a different quality at this point than at the stimulus-opening. If this should occur for any color when the fixation is at the 25° point, a lesser excentricity should be chosen. The sensitivity of the contrast-effect to change of illumination is not lessened to any considerable extent, for example, by taking a 20° instead of a 25° fixation-point. We have found the 25° point to be very

plane normal to the screen midway between the stimulus-opening and the fixation-point. The contrast-stimulus and the measuring disc thus receive equal amounts of light from the source to be measured.

In Fig. 1 is given a picture of the apparatus in the rough form in which it is at present used. At *S* is shown the screen which is illuminated in turn by the standard and comparison lights; at *B* the photometer bar; at *D* the measuring disc; at *L* the lamp to be photometered; at *M* the mouthboard;

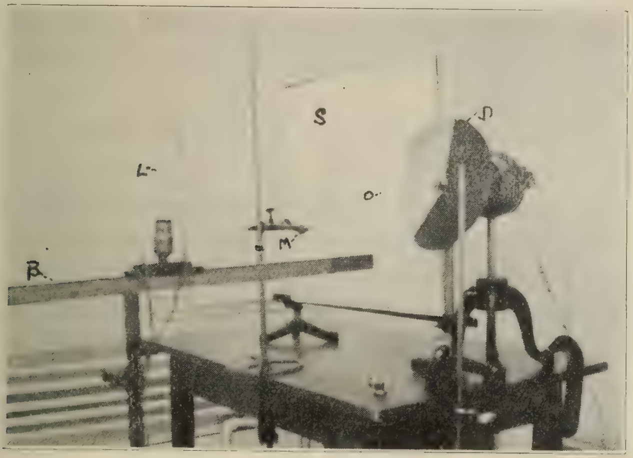

FIG. 1

and at *O* the opening filled with gray which is darkened in graded amounts by induction from the screen *S* as the amount of light received by it from the lamp *L* is varied. The screen *S* is supported by short rods screwed into heavy tripod bases. In order to provide for adjusting the height of the screen above the table the frame of the screen is fastened to the supporting rods by means of a collar and set screw. On the upper edge of this frame is attached a device for lining up the eye with the stimulus-opening *O*. This device consists of the following parts: A vertical arm carrying at its lower end a small circle 15 mm. in diameter extends

satisfactory, however. For a fixation-point we used a black knot on a gray thread, stretched from a point on the screen *S* to a rod in front and on the opposite side of the measuring disc.

down to the level of the stimulus-opening *O*. Attached to the vertical arm just above this circle is a horizontal arm 15 cm. long which carries at its outer end and at right angles to it a disc 22.3 mm. in diameter. The size and position of the disc, the circle, and the opening *O* and their distances from each other sustain such relations that when the eye is in position 25 cm. in front of the opening *O*, the line of regard contains the centers of the opening *O*, of the circle, and of the disc; and the inner edge of the circle is just contained within the stimulus-opening; and the edge of the disc is just contained within the circle. That is, in effect the device is a peep-sight arrangement, and the alignment described above is possible only when the eye is in such a position that the line of regard is perpendicular to the stimulus-opening, the circle, and the disc at their centers. The device is attached to the metal frame by means of a screw with a milled head, so that after the alignment is made it can be readily turned out of the road and clamped. In order that the distance of the eye may be accurately adjusted at the same time its alignment is made with the stimulus-opening, a measuring device is also provided. This device consists of a slender brass rod 25 cm. long fitted at either end with two short right-angled arms 5 mm. in length. On the end of one of these arms is a ring which is just larger than the stimulus-opening, and on the other is a brass disc of the same diameter as the ring, provided at its center with a large pupillary aperture. In adjusting the distance of the eye this disc is rested lightly against the forward surface of the eyeball and the ring against the screen *S* concentric to the stimulus-opening. When the position of the eye is once determined, a mouthboard is adjusted and clamped in position so that the observer's teeth fit into impressions previously made and hardened in wax. This fixes the relation of the observer's eye to the stimulus-opening *O*. All that is needed, therefore, at subsequent sittings to bring the eye again into this relation, is to fit the teeth into the impressions on the mouthboard. As stated above, the photometer bar when adjusted stands in a plane normal to the screen *S* and midway between

the stimulus-opening and the fixation-point. This guarantees that the stimulus-opening and the measuring-disc at the fixation-point shall receive equal amounts of light from the lamp on the bar. The nearer end of the bar is placed at a distance below the level of the center of the stimulus-opening and fixation-point equal to the height of the center of the filament of the lamp above the bar. Owing to the fact that the head may cast a shadow on the stimulus-opening when the bar is horizontal, the rear end of the bar is raised until the stimulus-opening and the screen for some distance around are free from shadow for any position of the lamp on the bar that may be needed to obtain the photometric balance. In order to provide for this tilting, the bar is made adjustable in height. It is supported on two heavy tripod bases each carrying a vertical stem made of hollow tubing split at the upper end and provided with collar and set screw. Into these tubes fit rods attached to the photometer bar by means of hinge joints. This arrangement permits of an independent adjustment of the height of the two ends of the bar. In order that a given amount of slant may be reproduced at any subsequent observation, an attachment is provided to indicate the angle which the bar makes with the vertical. This consists of a graduated half circle attached just above the hinge joint to the supporting rod furthest from the screen. On this rod just below the hinge joint is fastened a pointer. When the further end of the rod is raised this half circle is rotated past the pointer and the amount of rotation may be directly read from its graduated limb. Since the angle at which the bar is tilted is kept the same for the comparison and standard lights, the tilting interferes in no way with the accuracy of the photometric balance or the application of the law of squares to the determination of the relative luminosities of the standard and comparison lights.[1]

[1] We hope soon to use the principle upon which the method is based in connection with apparatus which will be more conveniently applicable to the general needs of the photometrist than is the rough device which is described above. One of the improvements which we expect to make, for example, is to eliminate the need of a slanting bar. For while the slanting bar does not interfere with the establishment of a correct photometric balance at the screen, it is not the most favorable condition under

The method is applied as follows: The observer's eye is lined up with the stimulus-opening in the manner described above and the contrast stimulus is put in position. The standard lamp is placed on the photometer bar at a given distance from the screen, the eye is turned out to the fixation-point and the sectors on the measuring disc situated just back of the fixation-point are adjusted by means of a number of separate judgments to match the gray at the stimulus-opening darkened by contrast.[1] The relative value of these sectors becomes the index of the illumination of the screen for the standard lamp at the given distance. The standard lamp is then removed, the comparison lamp is placed on the bar, and its position is adjusted

which to operate all types of lamps. This should not be difficult to do by moving the observer farther from the screen and using a correspondingly larger stimulus-opening and a greater linear distance from this opening to the fixation-point.

[1] That is, with the change in the amount of light falling on the photometer head made up of gray stimulus and surrounding screen of white, there is a change in the amount by which the gray stimulus is darkened by contrast from the surrounding screen. This amount is recorded on the measuring disc directly behind the fixation-point, by adding a sector of black to the gray sector, which was chosen, it will be remembered, of the brightness of the gray stimulus uninfluenced by contrast. The value of this black sector thus becomes the fixed index of the amount of light falling on the screen in any given case. In short, with a given brightness relation of contrast stimulus to surrounding screen, there is a finely graduated scale of contrast values inversely correlative with the amounts of light falling on the screen. That is, with a large amount of light or high illumination of the screen, the amount of contrast induced is low; with a small amount of light falling on the screen the amount of contrast induced is high. The amount of change of the illumination of the screen needed to produce a noticeable change in the amount of contrast induced is very small indeed and because of this the method possesses a high degree of sensitivity. So far as we are able to determine, the amount of change in this illumination required to produce a just noticeable change in the contrast sensation is no greater than is needed to produce a just noticeable change in the positive sensation under the best conditions that have been as yet devised in photometric work for making the judgment, namely, the conditions presented by the Lummer-Brodhun photometer heads of the most improved type when the lights compared are the same in color quality. If this were not true, the method could not show, as it does, as great sensitivity for lights either the same or differing in color quality as does the equality of brightness method for lights of the same color quality. Also so far as we have been able to determine there is no greater variability in the eye's sensitivity to contrast from day to day than there is in its sensitivity to brightness itself. That is, photometric determinations by this method of a given light density on the screen show a very small mean variation from day to day, quite comparable in fact, with the mean variation found in judgments of brightness equality, when there is no difference in color quality to confuse the judgment. There is, moreover, so far as we have applied the method, a comparatively small variation for different observers.

until the contrast-stimulus again just matches the measuring disc. Since the proportion of sectors has not been changed from that which was determined for the standard lamp, it can be assumed that the illumination of the contrast screen is again of the same value it was for the standard lamp at the given distance. The comparative luminosities of the two light

TABLE I

SHOWING A COMPARISON OF THE RESULTS OBTAINED BY THE CONTRAST AND EQUALITY OF BRIGHTNESS METHODS

Source of Colored Light[1]	Color	Distance of White Light Giving Equality of Illumination		Sensitivity or Amount of Change that Can be Detected by				Precision or the Mean Deviation from the Average			
		Equality of Brightness Method	New Method	Equality of Brightness Method		New Method		Equality of Brightness Method		New Method	
		Cm.	Cm.	Cm.	Percentage (Candle-power)	Cm.	Percentage (Candle-power)	Cm.	Percentage (Candle-power)	Cm.	Percentage (Candle-power)
87 cp. 41 cm. distant from photometric screen	Red	66.1	66.6	2.0	5.6	0.5	1.3	1.1	3.2	0.20	0.55
	Blue-green	59.5	59.5	2.5	7.85	0.5	1.65	1.5	4.85	0.22	0.97
52 cp. 38 cm. distant from photometric screen	Red	82.2	82.2	2.1	5.0	0.5	1.1	1.1	2.5	0.20	0.41
	Blue-green	70.9	70.5	4.0	10.4	0.5	1.4	2.0	5.5	0.25	1.1
13 cp. 38 cm. distant from photometric screen	Red	160.6	160	3.0	3.7	0.5	0.65	1.6	1.9	0.23	0.3
	Blue-green	134.5	134.9	4.0	5.7	0.5	0.76	2.2	3.2	0.24	0.46

sources, thus, can be computed directly by the law of squares from distance readings on the photometer bar. The advantage of the method for color photometry is, as has already been pointed out, that in the judgment in case of both the standard and comparison lights, the surfaces, the brightness values of which are being compared, are both illuminated by the same light. The eye is thus never compelled to make its judgment of two surfaces differing in color quality. The method is in fact almost if not quite as sensitive for the

[1] The colored lights were obtained in these experiments by means of the Wratten and Wainwright filters inserted in openings in the front of lamp-houses. The red filter used transmits the spectrum from .768 μ to .65 μ; and the blue-green from .52 μ to .465 μ.

photometry of lights differing in color quality as it is for the photometry of lights of the same color quality or for colorless light; and its sensitivity for lights of the same color quality or for colorless light compares very favorably, by test, for the same observer with photometers of the best Lummer-Brodhun type. The indirect vision judgment, it may be said, however, presents more difficulty to the unpractised observer than is afforded by the flicker judgment, but this difficulty yields rather readily to practice. The method has been in almost daily use in our laboratory for four years. It has, for example, been employed exclusively for the standardization of the illumination of our optics-room in the determination of color sensitivity.

Table I. has been prepared to show a sample of a comparison of the results of this method and the equality of brightness method. These results are typical. They report the average of twenty-five determinations. Sensitivity and the average deviation or precision are expressed both in divisions of the photometer bar and in percentage candle-power. The lamps used for this work were standardized by the New York Electrical Testing Laboratories. They were operated on a storage battery circuit.

With some modifications the contrast principle described above can be used for the determination in terms of pigment standards of the white-black value of colored papers for a given degree of illumination of the papers. The method of doing this can perhaps best be explained by comparing it with the method just described. In this method, it will be remembered, we determined how much contrast would be induced by one surface upon another of a lower coefficient of reflection when a given amount of light was incident upon the two surfaces, and used this amount of contrast as an index of the amount of light falling upon the two surfaces in establishing the photometric balance, or equality of illumination at the screen. Here the relation of coefficient of reflection of the screen to the stimulus is fixed and the amount of light falling on the screen from the comparison lamp is varied until the right amount is obtained to give the photometric balance with the

standard lamp. In the determination of the white-black value of a colored paper under a given illumination, the situation is a little different. The amount of light falling on the screen is kept constant and the relation to the screen of the pigment standard which is to express the white-black value of the color, must be varied until the right one is obtained. Here again we find out how much contrast is induced by one surface upon another of a lower reflection coefficient, in this case the colored paper; and this amount of contrast is taken as an index of the brightness relation of the colored paper to the surface of higher reflecting power, the screen *S* in Fig. 1, for the given intensity of illumination. The problem thus becomes to determine what gray sustains the same brightness relation to the screen *S* as does the colored paper. This gray should represent the white-black value of the color.

In detail the method is as follows: The stimulus-opening *O* is filled with the colored paper for which the determination is to be made and a disc of the same color is made a part of the measuring disc. The fixation is taken and black is added to the color on the measuring disc until it is sufficiently reduced in brightness to match the stimulus color darkened by contrast. The amount of black that has to be added becomes the index of the amount of contrast induced and therefore of the brightness difference between the screen *S* and the colored paper for the degree of illumination used, and is kept constant during the remainder of the work. In order to be able to find out what gray differs as much in brightness from the screen as does the colored paper, a disc made up of variable proportions of white and black is substituted for the colored stimulus behind the screen; and a sector made up of variable proportions of the same white and black, for the colored sector on the measuring disc. The white and black are then varied in proportions which are carefully kept equal for stimulus and sector until a match is obtained. When this match is gotten the relative amounts of white and black either in the stimulus disc or the substitute sector on the measuring disc should give the gray value of the color for the illumination employed. That is, there is obviously only one

gray that could be used in place of the contrast stimulus and in the substitute sector in the measuring disc which would satisfy the conditions of the experiment, and that is a gray having the luminosity or white-black value of the color originally used. It is scarcely necessary to caution that throughout the determination the light falling on the screen, the stimulus and the measuring disc must be kept constant. Care must be taken also in this case not to take the fixation so far from the stimulus-opening that a color difference is present between stimulus and measuring disc.

If the determinations are wanted in photometric units they can be gotten by the equality of brightness method from the grays which have been equated with the colors. A convenient instrument to use for this purpose is the Sharp-Millar portable photometer with its scale calibrated to give results in terms of candle-power per sq. in. The calibration can be readily made by the experimenter from a magnesium oxide surface with a known amount of light falling on it. If the light incident on the grays is daylight, the same difficulty will be experienced with the Sharp-Millar photometer, however, which was mentioned earlier in the paper, namely, the two halves of the photometer field will differ in color quality due to the fact that the carbon standard in this instrument gives a light rich in the long wave-lengths.

[1] In discussing the application of this method to the determination of the brightness of colored papers, reference should probably be given to the discussion of the Talbot-Plateau law in the paper preceding this. (See Ferree and Rand, 'A Preliminary Discussion of the Deficiencies of the Method of Flicker for the Photometry of Lights of Different Color,' *Psychol. Rev.*, 1915, 22, pp. 149–150.)

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A SPECTROSCOPIC APPARATUS FOR THE INVESTIGATION OF THE COLOR SENSITIVITY OF THE RETINA, CENTRAL AND PERIPHERAL

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The need has long been felt in physiological and psychological optics for better methods of specifying and standardizing the stimulus. In an adequate specification and standardization of the stimulus for work in these fields, three points are involved. Means must be had (1) of securing a small range of wave-lengths and of stimulating with them any part of the retina; (2) of determining accurately the values of the wave-lengths employed; and (3) of specifying the amounts of light used. In the present series of papers apparatus will be described with which it is, comparatively speaking, easily and conveniently possible (1) to stimulate any part of the retina with the light of the spectrum and to control as desired the conditions of preëxposure and surrounding field; (2) to control the amounts of light used within the small gradations needed for threshold and just noticeable difference determinations; and (3) to specify in C.G.S. units in any case in which it is wished the amount of light used. This work was begun and announced three years ago as the logical completion of work published at that time[1] and has

[1] See Rand, G., 'The Factors that Influence the Sensitivity of the Retina to Color: A Quantitative Study and Methods of Standardizing,' *Psychol. Rev. Monog.*, 1913, *15*, No. 1, 166 pp.; and Ferree, C. E., and Rand, G., 'A Note on the Determination of the Retina's Sensitivity to Colored Light in Terms of Radiometric Units,' *Amer. Journ. of Psychol.*, 1912, XXIII., pp. 328–332.

If more time has been taken to accomplish what we have here to present than seems justifiable, we beg to point out that the work has been in many respects pioneer in character and that the difficulties on the radiometric side had not yet been overcome by the physicist at the time we began our work. We have also been greatly diverted by the pressure of other work.

The apparatus has been greatly simplified from its original construction. As it

involved the construction of a new type of campimeter, spectroscope, apparatus for the regulation of the amount of light used applicable to the spectroscope employed, and radiometric apparatus non-selective in its response to wave-length and sufficiently sensitive for the purpose in hand. The apparatus included under the first three of the above classes was constructed under direction by our department mechanician and should be within the technical capabilities of any good college mechanician. The description of this apparatus will form the subject matter of the present paper. For the radiometric apparatus we are indebted to Dr. W. W. Coblentz, radiometric specialist for the Bureau of Standards. Believing that the sensitivity of the thermopile could be increased by enlarging the area of the receiving surface and wanting to measure for at least one color all the light energy falling on the stimulus-opening in our campimeter screen rather than attempt to calculate it from one or more linear elements in this surface, we took up with Dr. Coblentz the feasibility of constructing surface thermopiles. He was asked to construct for us a surface thermopile having a receiving surface 16 mm. square, a trifle larger than the opening in our campimeter screen.[1] By means of this thermopile and one of the linear type we have been able to measure the light at three places—at the analyzing slit, at the campimeter opening, and at the eye. The use that is made of these measurements in the color investigation will be stated in a later paper.

Description of Apparatus

For the sake of convenience the apparatus may be described under three headings: (*a*) an apparatus for getting

now stands it is comparatively simple in form; it is not difficult to operate, and is, we believe, within the financial and technical possibilities of any laboratory in which serious work is being done in the optics of color. There is no work known to us in the investigation of color sensitivity in which light of a standard quality and intensity is needed to which this or a similar apparatus can not be adapted. On the spectroscopic side at least we hope it will prove sufficiently feasible and practicable to render undesirable the use of colored papers and filters in much of the work that is now being done in the optics of color.

[1] See Coblentz, W. W., 'Instruments and Methods Used in Radiometry'—II. *Bulletin of the Bureau of Standards*, 1912, IX., p. 22, ff.

the light stimulus of spectrum purity and of exposing different parts of the retina to this stimulus under any conditions of surrounding field, preëxposure, etc., that may be desired; (*b*) an apparatus for varying the intensity of the stimulus within the limits needed for threshold and j.n.d. work; and (*c*) an apparatus for measuring the intensity of the stimulus in terms of common or C.G.S. units.

1. An apparatus for getting a light stimulus of spectrum purity and of exposing the different parts of the retina to this stimulus under any conditions of surrounding field, preëxposure, etc., that may be desired.

To design an apparatus which will combine all the above features and which can besides be easily and conveniently operated is a task which has presented considerable difficulty.[1] Dreher[2] and Abney,[3] for example, have each described apparatus devised to accomplish a part of what is outlined above, but the apparatus of neither would at all serve the purpose that has impelled us to take up anew the problem of the construction of apparatus.

[1] A statement of the points needed by an apparatus by means of which all the factors influencing the sensitivity of the retina to colored light may be controlled and which will have besides a wide range of serviceability is, in the belief of the writers, as follows. (1) It must provide an accurate means of separating out the desired ranges of wave-lengths throughout the spectrum. (2) Means must be provided for directing these wave-lengths to any part of the retina that is desired. (3) Provision must be had for controlling the brightness of the field surrounding the color and the brightness of the preëxposure. (4) The apparatus must be available for use in a light as well as in a dark room, else (*a*) the influence of the brightness of the surrounding field and of the preëxposure upon the response of the retina to the different colors can not be eliminated from the investigation when wanted; and (*b*) a large part of the work in the optics of color can not be done, namely, the investigations of response under different degrees of illumination. (5) A method of presenting the light to the eye must be had which will give the effect of a surface or field variable in shape and size that may be imaged on the retina. (6) The method of presentation must be such as to allow of no admixture of light from the room with the range of wave-lengths needed for the stimulus, and it must be as little as possible wasteful of light, else a sufficient range of intensity can not be had. (7) A beam of colored light should be provided of such intensity that its energy value per unit of cross section can be specified when desired at the point of entrance of the light into the eye.

[2] Dreher, E., 'Methodische Untersuchung der Farbentonänderungen homogener Lichter bei zunehmend indirektem Sehen und veränderter Intensität,' *Z. f. Sinnesphysiol.*, 1912, *46*, pp. 1–82.

[3] Abney, W. deW., 'The Sensitiveness of the Retina to Light and Color,' *Philos. Trans. of the Roy. Soc. of London*, 1897, Ser. A, *190*, pp. 155–195.

A schematic representation of the apparatus under this heading is shown in the diagram in Fig. 1. It consists in

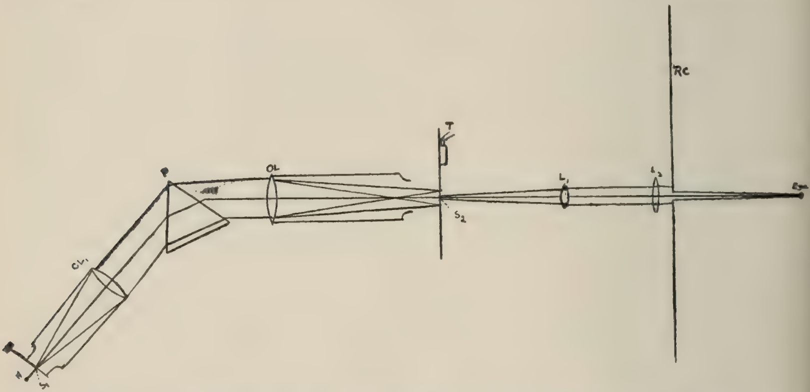

FIG. 1. Showing the Path of the Light from the Source to the Eye.

general of light source (N), spectroscope (Sp), micrometer slit (S_2) for separating out the wave-lengths needed for the colored stimulus, rotary campimeter (RC), collimating lens (L_1) for rendering parallel the beam of light emerging from the analyzing slit (S_2), and focusing lens (L_2) for bringing this beam to a focus on the pupil and for shifting the image formed to follow the pupil as the eye takes fixation at different degrees of excentricity.

It is scarcely needful to call to mind that one of the chief difficulties in devising a peripheral vision spectroscope has been to secure a means of throwing the colored light on the excentric portions of the retina. Dreher, for example, has tried to do this with limited success by holding the eye stationary and by reflecting the light to the different portions of the retina by a system of mirrors. By this means so much light is lost by reflection that the device would be useless for our purpose because we wish to be able to radiometer the light which finally reaches the eye. Moreover the difficulty in making the adjustments and the impossibility of making fine adjustments even for the different portions of the retina in the same meridian render the apparatus practically useless for extended work. Also the ordinary campimeter precautions with regard to the control of the brightness of the

surrounding field and preëxposure can not be taken nor can the apparatus be used in an illuminated room without the admixture of a great deal of light from the room with the wave-lengths selected for the stimulus. So far as we know, no attempt has yet been made to adapt the spectroscope to the campimeter, at least not in such a way that any meridian of the retina can be worked in easily and conveniently from center to periphery and an accurate control be had at every step of the brightness of the field surrounding the stimulus and the preëxposure.[1]

[1] The hollow hemisphere, for example, used by Abney can scarcely be considered a campimeter for it was not designed for exercising any control over the brightness of the surrounding field. The apparatus was designed solely for dark-room work and was called by him a perimeter. The practical impossibility of uniformly controlling the brightness of the field surrounding the stimulus by means of an opaque campimeter screen hemispherical in shape was shown by one of the writers (Ferree) in a previous article. ('A Note on the Rotary Campimeter,' *Psych. Rev.*, 1913, *20*, pp. 373–378.)

Abney describes two devices for exposing the peripheral retina to the light of the spectrum. Both are for use in the dark room. The first consists of a perimeter, the graduated arm of which is painted white, and the following auxiliary apparatus. Below the eye is placed "a small mirror on a ball and socket joint which by means of an arm causes a beam of light falling on it to be cast in any direction that is desired." The monochromatic light for the stimulus is gotten by means of an instrument which he calls his "color patch apparatus." The light passes from this apparatus to the mirror on the ball and socket joint which reflects it to the different points on the arm of the perimeter. In this way patches of color which serve as the stimuli for the eye in the color investigation are formed at different degrees of excentricity on the perimeter arm. That is, with regard to the method of securing the stimulation of the peripheral retina, this apparatus is of the usual type. The eye is held stationary and the retina is stimulated from center to periphery in a given direction by causing the colored stimulus to pass from the center to the periphery of the field of vision in the opposite direction. In his second apparatus, also called a perimeter by him, a hollow white hemisphere made of papier mâché is employed instead of a rotating arm. In the center of this surface is a circular aperture $1\frac{1}{2}$ in. in diameter to admit the stimulus light. To give the effect of a colored surface to this aperture when illuminated from behind with colored light, it was filled in with glass ground on both sides. In order that the shape and size of the stimulus may be varied, additional special apertures are provided which are placed as desired in the path of light immediately behind the fundamental aperture. As before, the color patch apparatus is used as the source of the stimulus light. The method of securing the excentric stimulation of the retina, however, is just the reverse of that described before. That is, the colored stimulus is kept in a fixed position and the eye follows a phosphorescent point which is moved from the center to the periphery of the hemisphere in the meridian in which the investigation is being made.

Neither of Abney's devices would have answered our purposes for the following reasons. (1) Neither is adapted for use in a light room. (2) Provisions for the

One of the difficulties encountered in attempting to do this is that when the eye is turned to take an excentric fixation, the pupil is rotated out of the beam of light. To overcome this, we have taken advantage of the simple fact that when the axis of a double convex lens is displaced from the axis of the beam of light, the image of the light is displaced in the same direction in which the lens is moved. Therefore, by moving the focusing lens (L_2) an appropriate amount in the direction the eye is moved in taking its excentric fixation, the beam of light can always be kept focused on the pupil, while no light energy is lost in the operation, at least not enough to be detected either by the eye or by the thermopiles, linear or surface, that we are now using. That is, in the apparatus shown in the diagram, the lens (L_2) which focuses the light on the eye, is mounted on a rack and pinion operating in the line of the fixation-arm of the campimeter. When a given meridian is to be investigated, the fixation-arm is turned into this meridian and the light is always kept focused on the pupil of the eye by means of fine changes in the position of the lens made possible by the rack and pinion adjustment.[1]

control of surrounding field and preëxposure are lacking. And (3) the loss of light is so great and the method of presentation is such that the intensity of the light entering the eye could not be measured.

[1] One of the objects in devising this means of presenting the stimulus light to the eye has been to get an apparatus that could be used in a well illuminated room, for only under these conditions, as has been shown in previous articles (see 'A Note on the Determination of the Retina's Sensitivity to Colored Light in Terms of Radiometric Units,' *Amer. Jour. of Psychol.*, 1912, *23*, pp. 331–332; 'The Effect of Changes in the General Illumination of the Retina upon its Sensitivity to Color,' *Psychol. Rev.*, 1912, *19*, pp. 463–490; 'The Factors that Influence the Sensitivity of the Retina to Color; A Quantitative Study and Methods of Standardizing,' *Psychol. Rev.* Monog., March, 1913, pp. 135–166) can the influence of the brightness of the surrounding field and of the preëxposure be eliminated from the investigation. Obviously a serious difficulty in working in an illuminated room is to get a method of presenting the stimulus to the eye that will give the effect of a colored field and prevent the admixture of light from the room with the wave-lengths which are needed for the investigation. The following methods may be used in dark-room work to get the effect of a colored field or surface to image on the retina. (1) Light of the desired range of wave-lengths is allowed to fall on a diffusely reflecting surface which is non-selective in reflection of wave-length. The standard reflecting surface for purposes of this kind is prepared from magnesium oxide deposited from the burning metal. Such a surface properly prepared has a high reflection coefficient approximately 90 per cent., and possesses

The Source of Light.—The requirements of a source for our purpose are (*a*) that it should give a light in which all the wave-lengths are represented in sufficient strength both for the needs of the investigation of color sensitivity and for radiometric standardization; and (*b*) that the light emitted shall be as constant as possible in intensity and spectro-radiometric composition. After trying many light sources we have finally adopted as best for our purpose the Nernst filament. This filament, after having been properly seasoned,

the additional advantage that it can easily be kept fresh. And (2) light of the desired composition is allowed to fall on a diffusely transmitting surface also non-selective, or approximately so, in its transmission of wave-length. These methods of getting the effect of a colored surface or field while serviceable within limits for dark-room work, have the following objections for our purpose. (*a*) Both kinds of surface would reflect the white light of the room—the magnesium oxide surface, for example, would reflect approximately 90 per cent. of the light falling on it. This effect, however, is reduced to a minimum by using a double convex lens in the manner employed by us. For when a parallel beam of light falls on the lens and the eye is placed at the focus, the lens fills uniformly with light, and, so far as we are able to determine, white light is not reflected to the eye from the surface of the lens in appreciable amounts under the conditions obtaining in our work. That is, the lens is placed 2.5 cm. behind the stimulus-opening and the whole spectroscope and lens system are enclosed up to the campimeter screen in a light-tight compartment. Under these conditions by exercising a little care in the selection of the position of the apparatus with reference to the distribution of light in the room, so little light is reflected from the lens to the eye that the presence of the lens can not be detected when the eye is in position before the stimulus-opening and no colored light is coming from the spectroscope. In other words, not enough white light is reflected from the lens to render it visible to the eye. (*b*) Both of these methods are very wasteful of light. That is, there is not only a comparatively high percentage of absorption of light by the types of diffusing media, but only a small percentage of the light coming from any point or unit of the surface of these media enters the pupil of the eye. Thus there is not the possibility of getting the wide range of intensities of light needed to give the apparatus maximum serviceability for the investigation of color sensitivity. Furthermore, we are desirous of being able to specify in radiometric units the amount of light per unit area in the cross section of the beam of stimulus light at its entrance into the eye. This would be a very difficult task indeed with either of the two methods of presenting the stimulus light to the eye mentioned above. Its accomplishment, however, is not at all difficult by the method we have adopted. That is, instead of the light spreading from the stimulus-opening as if emanating from a source, it is concentrated into an image on the pupil of the eye, an image in this case of the analyzing slit. (S_2, see pp. 250, 261 and Figs. 2 and 3.) The amount of energy concentrated into this image can easily be determined by direct measurement with our radiometric apparatus for any of the wave-lengths used by us as stimuli, and the amount per unit area be estimated; further, if an artificial pupil were used, or the substitute to be described in a later paper, see *Psychological Review*, 1916, September number, the total amount of light entering the eye could be determined in C.G.S. units.

gives a light which changes comparatively little through long intervals of time. It has the advantage, moreover, that its shape well adapts it for use with the slit of the spectroscope, *i. e.*, the shape is such as to make it possible to utilize for the illumination of the face of the prism a relatively large proportion of the light emitted. Also by increasing the length of the filament and collimator slit, it is possible to increase in direct ratio the amount of light falling on the face of the prism. When in use, in order that no light shall be lost in passing through one or more condensing lenses, the filament

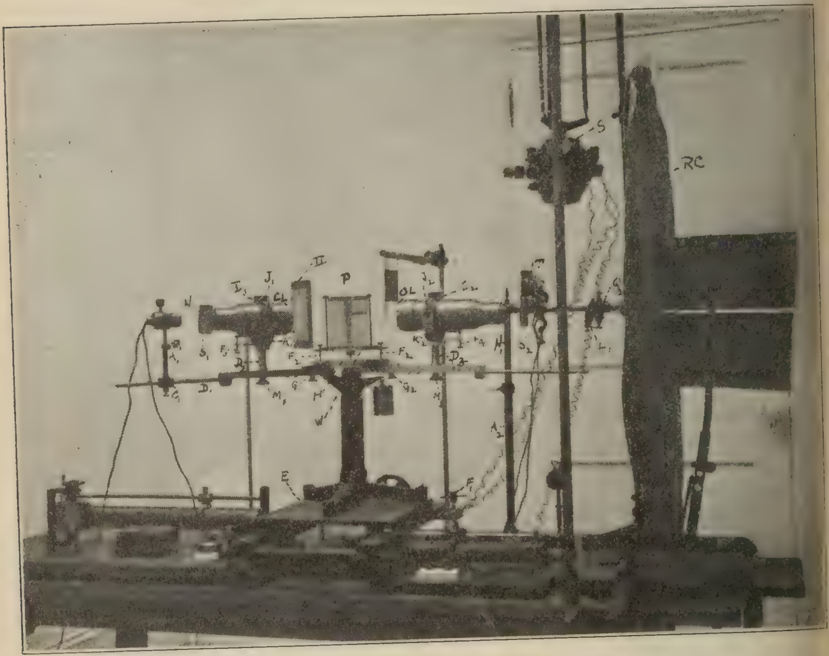

FIG. 2. Showing the Apparatus Grouped for Work—light source, spectroscope, thermopile, and rotary campimeter with its auxiliary lens system. In order that all stray light either from the general illumination of the room or by reflections from the Nernst glower be eliminated, the spectroscope and lens system are, when in use, enclosed from just in front of the Nernst to the campimeter screen in a light-tight compartment.

is mounted as closely as possible to the jaws of the slit. It is shown in position for work at (*N*) in Figs. 2 and 3. The filament is mounted in a lamp socket fastened to an upright

(A_1). In order that the height of the filament shall be adjustable this upright consists of a short rod sliding in a tube fitted with collar and set screw (B) which permits of a movement of the socket up and down, also to right and left. The upright (A_1) is fastened to the horizontal support (D_1) ex-

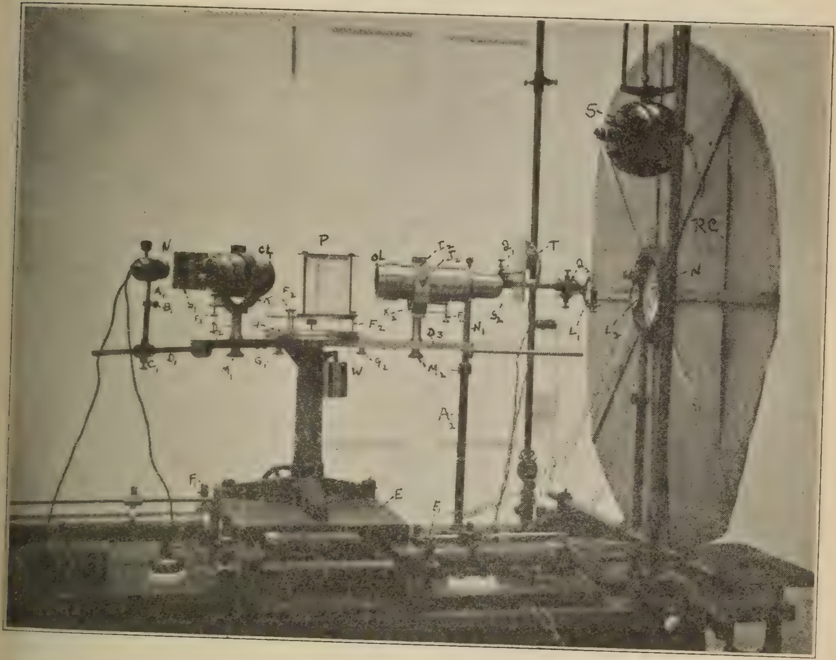

FIG. 3. Showing a Second View of the Apparatus Grouped for Work.

tending out from the collimator arm of the spectroscope by a clamp and set screw (C_1) which permits of the motion of the socket to right and left and to and from the collimator slit. The Nernst filament used by us is designed to be operated at 110 volts on a D.C. current, and has a carrying capacity rated at 1.2 amperes. When operated at its maximum capacity on a direct current, we have found, however, that the life of the filament is short. Satisfactory results have been obtained by us only when it is operated at or below 0.6 amperes. In series with the ballast, therefore, which is ordinarily used for the reduction of the current from the line and to compensate for the change in the resistance of the

Nernst material as its temperature varies, we have found it necessary to use additional resistance. This resistance is needed not only to cut down the current to the desired value, but to correct for fluctuations in the line. Two coils are employed, one coarse and one fine. The former is used to cut down the current to approximately the desired value, and the latter to correct for the fluctuations in the line. Both are in the form of adjustable rheostats. The second is of special construction to give the small changes needed. It consists of a cylindrical coil of wire wound on an insulated core of brass tubing and is operated by a screw motion in such a way as to give the effect of a slider on a single wire. This rheostat is described in greater detail on p. 275. It is not on the market but can readily be constructed to order by a laboratory mechanician. The finely graduated control afforded by it not only makes it possible to correct for fluctuations in the line, as is stated above, but also to compensate for the slow decrease in the carrying capacity of the Nernst material with use. The current consumed is measured by a Weston ammeter graduated to 0.02 amperes. Operated with this type of control the light flux obtained from the Nernst may be kept constant within the limit of change that can be detected either by the radiometer or the eye.

The Spectroscope.—In addition to the usual features attaching to a good spectroscope, our instrument was designed especially to meet the following needs. (1) To answer all the purposes for which a source of colored light may be used in the investigation of color sensitivity, a wide range of intensity is needed. In order too that an adequate radiometric standardization be made, it is especially desirable that light of high intensity be available. (2) If the spectroscope is to be used in conjunction with a campimeter, it is necessary that the objective arm remain in a fixed relation to the stimulus-opening of the campimeter screen and that some convenient and accurate means be had of changing the wave-lengths without changing the position of the objective. The first of these needs was met by employing a collimator slit long enough to admit the amount of light needed, and a

prism and lenses large enough to take care properly of the amount of light admitted. The second point has been met by us in the two following ways, one of which is technically more correct perhaps than the other. (*a*) The spectroscope was mounted on a stationary base supported by levelling screws. In fixed relation to this base a slit (S_2) was permanently mounted to separate out the wave-lengths which are to fall on the stimulus-opening in the campimeter screen. In order to be able to change the wave-length of the light falling on the slit (S_2) the stationary base carries a track along which the whole spectroscope may be shifted by very small amounts. This movement is made by means of a screw of fine thread turned by a wheel $4\frac{1}{2}$ inches in diameter. This track and the base of the spectroscope carry a Vernier scale graduated to 1/50 of a mm. by means of which any previous setting may be accurately reproduced, and in terms of the readings of which the spectroscope may be calibrated in wave-length. This method of changing wave-length not only provides abundantly for small changes in wave-length but it obviates any necessity for readjustment of the collimator arm which would be the case were the wave-lengths changed, for example, by rotating the prism. In case the wave-length is changed by this device, the prism is set for minimum deviation for the D-line, and this adjustment is kept throughout. An adjustment which gives minimum deviation for the D-line alone is generally considered by spectroscopists to be adequate for the work in the visible spectrum when the light is passed through only one prism. Kayser, for example, says:[1] "Bei den Apparaten mit nur einem Prisma verzichtet man für gewöhnlich darauf, alle Wellenlängen unter dem Minimum zu beobachten, sondern stellt das Prisma fest auf, so dass etwa die D-Linien unter dem Minimum durchgehen. Die Dispersion ist bei einem Prisma so gering, dass dies gewöhnlich genügt. Das ist aber nicht mehr der Fall, wenn man über die Grenzen des sichtbaren Spectrums hinausgeht, und so hat vielleicht zuerst Langley bei seiner Untersuchung des ultrarothen Theiles

[1] 'Handbuch der Spectroscopie,' Bd. I., p. 510.

des Sonnenspectrums an einem Apparat mit einem Prisma eine Vorrichtung beschrieben, welche automatisch das Minimum erhält, und welche wegen ihrer Einfachheit seitdem oft verwandt wird." (*b*) In order that minimum deviation may be had automatically for all wave-lengths falling on our analyzing slit, one of our spectroscopes was built with a minimum deviation attachment.[1] A schematic representation of this attachment and the prism in position for use is shown in Fig. 4. In this figure, *P* represents the prism so placed on the prism table that its refracting angle is bisected by one of the radii of the table; *PB* and *PA* represent respec-

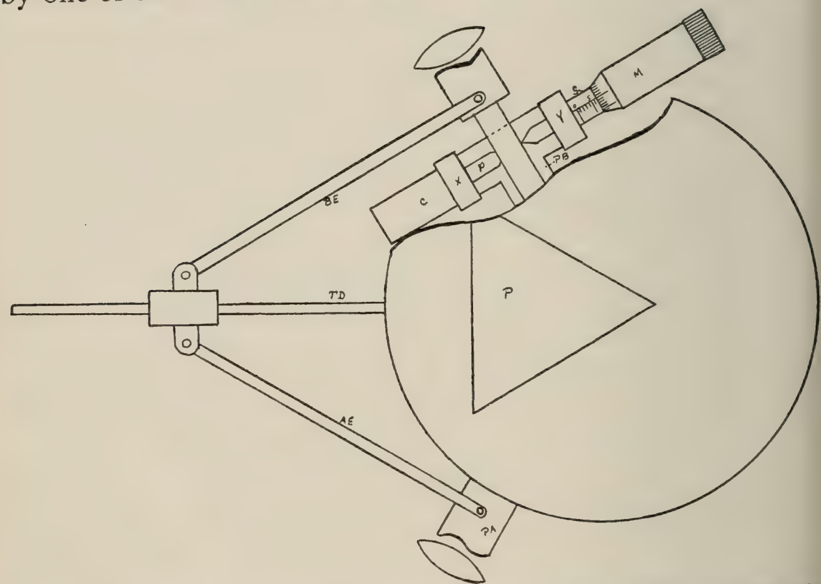

FIG. 4. Showing the Prism Table with Its Auxiliary Minimum Deviation Attachment.

[1] This attachment is a modified form of a device apparently used first by A. Cornu in 1873. He does not describe the apparatus, however, until ten years later ('Sur un spectroscope à grande dispersion,' *J. de Phys.*, 1883 (2), *2*, pp. 53–57). The first suggestion of such a device seems to have been made by Mascart ('Recherches sur le spectre solaire ultra-violet, et sur la détermination des longueurs d'onde,' *Ann. école norm.*, 1864, *1*, pp. 219–272). See also S. P. Langley, 'The Selective Absorption of Solar Energy,' *Amer. J. of Sc.*, 1883 (3), *25*, pp. 169–176, *Philos. Mag.*, 1883 (5) *15*, pp. 153–183, *Ann. Chim. et Phys.*, 1883 (5), *29*, pp. 497–542, *Wied. Ann.*, 1883 *19*, pp. 226–244, 384–400; B. B. Donath, 'Bolometrische Untersuchungen über Absorptensspectra fluorescerender Substanzen und ätherischer Oele,' *Wied. Ann.*, 1896 *58*, pp. 608–661; and F. L. O. Wadsworth, 'Fixed-arm Spectroscopes,' *Philos. Mag.* 1894 (5), *38*, pp. 337–351.

tively the collimator and objective arms which are fastened to the stem of the spectroscope independent of the prism table; *TD* represents an arm fastened to the prism table in such a position as to be continuous with the radius of the table which bisects the refracting angle of the prism; *AE* and *BE* represent two rods of equal length which connect *PA* and *PB* at points equidistant from the center of the table to a collar which is free to play back and forth along the arm *TD*. *M* is a micrometer screw with a graduated cylindrical head, which is used to move the collimator arm through the small angles needed to give the change of wave-length. Opposed to this screw is a plunger *p* working against the spring in the case *C*. When the screw advances it moves the collimator arm forward and when it recedes the collimator arm is made to follow it by the push of the plunger *p*. The screw and plunger are supported by a curved arm coming off from the stem of the spectroscope, which can be clamped rigidly in any position which may be desired. This arm ends in two right-angled extensions, one of which carries the screw and the other the plunger. Between *X* and *Y*, the vertical arms of these extensions, the collimator arm is moved to give the change of wave-length. The micrometer screw passes through a fixed sleeve *S* graduated in fortieths of an inch. As the screw advances the cylindrical head telescopes on the sleeve *S*, one of the graduated spaces being traversed with each complete turn of the screw. The forward end of the cylindrical head is bevelled and on the circumference of the bevelled edge is a scale of equal divisions graduated in twenty-fifths of an inch. By means of this scale and the scale on the sleeve *S*, the advancement of the screw can be read in thousandths of an inch.

That minimum deviation is given automatically by this device to all the wave-lengths falling on the analyzing slit may be understood from the following considerations. In attaining minimum deviation the incident and emergent rays make equal angles with the normal to the refracting faces of the prism, therefore equal angles with the refracting faces themselves. When an adjustment is made for minimum

deviation for the D-line of the spectrum, for example, and the wave-length is changed by moving either the collimator or objective arms, the prism must be turned through half the angle through which the collimator or objective arm is moved if the wave-length traversing the axis of the objective tube is to be deviated the minimum amount. That is, for the prism to be set for minimum deviation the line bisecting the refracting angle of the prism will also bisect the angle made by the incident and emergent rays; hence if in changing the wave-length, the angle between the incident and emergent rays be changed a given amount by a movement of the collimator or objective arm, the prism must be moved through half that angle in order that the line which bisects its refracting angle will also bisect the angle made by the incident and emergent rays. The special purpose of the attachment described above, therefore, is to turn the prism through half the angle traversed by the collimator arm in changing the wave-length. This is attained by placing the prism on the table so that the radial arm *PD* bisects the refracting angle, and by connecting the moveable collar on the arm *PD* with the collimator and objective arms at points equidistant from the center of the prism table by rods of equal length (*AE* and *BE* of Fig. 4). Then when an adjustment is made for the D-line, and the collimator arm is moved through the angle needed to change the wave-length which falls on the analyzing slit, the arm (*PD*) turns through half that angle and takes up a position midway between the collimator and objective arms, and the part of the spectrum which falls on the analyzing slit is deviated the minimum amount in passing through the prism.[1]

[1] A constant deviation prism may be used also for getting automatically minimum deviation for all parts of the spectrum. Such a prism may be constructed by setting two 30° prisms against the faces of a right-angled totally reflecting prism; or the prism may be made in one piece in such a way that the four vertical faces enclose four angles of 90°, 75°, 135°, and 60° respectively. In using this type of prism the colli[illegible] mator and objective tubes are set permanently at right-angles to each other. When this is done and the prism is rotated about a vertical axis, the different portions [illegible] the spectrum are thrown on to the analyzing slit and the portion that enters it [illegible] any moment, will traverse the system at minimum deviation.

In the early part of our work we used a constant deviation prism of the Cass[illegible]

Following is a description of the parts and mounting of the spectroscope. The collimator slit (S_1) is 12 mm. long. Its width is adjusted by means of a micrometer screw fitted with a head graduated to read thousandths of a mm. The collimator lens (CL) is a Zeiss triple achromat, 180 mm. focal length, 60 mm. diameter; the objective lens (OL) is also a Zeiss triple achromat, 240 mm. focal length, 60 mm. in diameter. The prism (P) is 100 mm. high and has a refracting base of 85 mm. and a refracting angle of 60°. Owing to the large size required, a liquid (CS_2) prism has thus far been used. With the exercise of a reasonable amount of caution to keep the CS_2 free from impurities, this prism has given very good satisfaction. At present we see no good reason why its use should not be continued. The analyzing slit (S_2) is made adjustable in length. The range attainable varies from 0 mm. to 12 mm. A slit adjustable in length is employed in order that the amount of light entering the eye may be made independent of the natural pupillary aperture. (See 'A Substitute for an Artificial Pupil,' *Psy. Review*, 1916, —, September number.) So far it has been mounted on an independent base screwed to the table in a fixed relation to the base of the spectroscope and the stimulus-opening in the campimeter. If desired this base might be made a continuation of the base of the spectroscope. In order that the distance of this slit from the objective lens (OL) may be adjusted for the different focal distances for the different wave-lengths, the frame in which the slit is mounted is furnished with a rack and pinion adjustment.

In Figs. 2 and 3 is shown the mounting of the spectroscope. At E may be seen the platform and track on which moves the carriage bearing the spectroscope. The platform is supported on four upright somewhat pointed screws (F_1) which serve the triple purpose of leveling the apparatus, of

type which not only gives automatically minimum deviation but also the effect of a train of prisms; *i. e.*, the arrangement is such that the light is passed back and forth through the prism a number of times before it finally enters the objective tube. Cassie, W., 'Multiple Transmission Fixed-arm Spectroscopes,' *Philos. Mag.*, 1902, ser. 6, *3*, 449–457.) This prism was constructed to special order of the dimensions needed for our apparatus.

allowing an adjustment of 4 inches in height, and of preventing chance shifting of the position of the apparatus on the table.[1] To this movable platform is securely fastened the heavy stem and tripod base on which the spectroscope is mounted. The prism table of the spectroscope is shown at *W*. It has two adjustments. (*a*) With its supporting table it can be rotated in the horizontal plane to provide for the adjustment of the collimator and objective systems at the angle of minimum deviation and to allow for change of wave-length by the rotation of the prism if that should be desired. And (*b*) it is furnished with three leveling screws (F_2) by means of which it can be accurately leveled. The collimator and objective tubes are mounted on two horizontal arms (D_2 and D_3) which rotate about the upright stem on specially prepared collars. D_2 furnishes the support for the light source and the collimator tube, and D_3 for the objective tube. In order that these arms when adjusted shall be

[1] In the construction of the carriage and track great care was taken that there should be no play or free motion of the parts. This was necessary in order that for a given reading of the Vernier scale on the carriage and platform the axis of the objective should always sustain the same relation to the slit (S_2)—in other words that for a given reading the same wave-lengths should always fall on the slit.

The calibration of this Vernier scale was accomplished by means of a Hilger direct vision spectrometer which has a scale reflected across the upper half of the spectrum. Since wave-lengths can not be read directly from this type of instrument, a supplementary chart must be made in which are given the values of the different scale divisions in terms of wave-length. This was done as follows. Twenty-six points in this scale were identified with the bright lines given by potassium, strontium and cadmium arcs and by the mercury tube. The wave-lengths of these bright lines were obtained from Hagenbach and Konen's 'Atlas of Emission Spectra,' and from these values the curve of wave-lengths was plotted for the entire spectrum. For the calibration of the Vernier scale the Hilger spectrometer was then mounted behind the stimulus-opening in the campimeter screen, and the wave-lengths coming through for any given reading of the Vernier scale were determined.

The calibration of the graduated scale on the fixed sleeve and cylinder head of the minimum deviation attachment (p. 258–260) may be accomplished in a similar way.

In case the minimum deviation attachment is used and the changes of wave-length are produced by it, such precision in the construction of the carriage and track as is described above is of course not necessary. That is, the carriage and track, while devised in our particular apparatus primarily for changing the wave-length, is very serviceable for other purposes which do not require such careful construction. For example, we have found this feature to be very useful in lining up the instrument with other apparatus, especially when the work requires the objective arm to be fixed as is needed in our adaptation of the spectroscope to the campimeter.

held rigidly in place, they are firmly clamped to the supporting table by means of the metal pieces (G_1 and G_2) one end of each of which is milled down to fit in a groove in this table (H) and the other is clamped respectively to the arms (D_2 and D_3). The collimator and objective lenses are each mounted in brass telescope tubing provided with a rack and pinion for the adjustment of its length. In order that the axes of these tubes may be in the same horizontal plane the following provisions for leveling are made. The tubes fitted about one-fourth of their length from the larger end with collars (I_1 and I_2), are swung on trunions (J_1 and J_2) in U-shaped housings (K_1 and K_2) supported by small vertical pillars coming up from the horizontal arms (D_2 and D_3). The smaller end of each tube rests on a leveling screw (F_3 and F_4) threaded in a short horizontal stem coming out from the housings (K_1 and K_2), by means of the adjustment of which the axis of the tube may be brought into the proper position. When this position is attained provisions are made for clamping the tube firmly in place. In order that room may be allowed between the prism and the collimator and objective tubes for the introduction of apparatus for reducing the intensity of light or for any other purpose that may be desired, the vertical pillars carrying the tubes run in slots 10 cm. long cut in the horizontal arms (D_2 and D_3). When adjusted to the proper position the pillars are firmly clamped to the horizontal arms by means of the milled nuts (M_1 and M_2). The analyzing slit to separate out the wavelengths to be used for the colored stimulus is shown at S_2. The length of this slit may be made to vary from 0 mm. to 12 mm. Its width is adjustable by means of a micrometer screw fitted with a head graduated to read to thousandths of a mm. This slit is mounted vertically in an oblong brass frame, 12 cm. long and 6.5 cm. broad, carrying on each side a groove. In this groove slides a narrow brass plate on which is mounted a linear thermopile (T) with its receiving surface facing in the direction of the slit through a circular opening in the plate. During the color observation the plate and thermopile are raised out of the path of the beam of light

and clamped. For the energy measurements they are lowered to the level of the slit. In order to focus the different wave-lengths of the spectrum on the analyzing slit, a micrometer adjustment is provided to regulate the distance from the objective lens. The frame for thermopile and slit and the micrometer attachment are carried by an upright (A_2) which is mounted to one side of the path of the beam of light on a heavy independent tripod base screwed to the table. In order that there may be an adjustment of height, the upright consists of a tube 34 cm. long fitted at its upper end with a collar and set screw into which slides a steel rod (N_1) 38 cm. in length. The micrometer adjustment consists of a tube 30 cm. long and 15 mm. in diameter along the axis of which runs a finely threaded screw fitted with a milled head. In this tube is a beveled slot 5 mm. wide and 22.5 cm. long exposing the threaded screw. Telescoping the tube are two sections of tubing of larger bore (Q_1 and Q_2), 4.5 cm. in length, to the inner surfaces of which are screwed threaded pieces which extend down into the slot and engage the micrometer screw. As the micrometer screw is turned, these tubular sections move slowly along the screw. They are each fitted with collar and set screw which hold the horizontal rods supporting respectively the framework for the thermopile and the holder for the collimating lens (L_1). The collimating lens (L_1) is inserted in the path of the beam of light in order that the light emerging from the analyzing slit (S_2) may enter parallel the focusing lens (L_2) in front of the stimulus-opening in the campimeter screen. This lens has a diameter of 40 mm. and a focal length of 140 mm. Obviously if it is to act as a collimator for all the waves of light emerging from the slit (S_2), its distance from the slit must always be kept equal to its focal length. That is, when the distance of the slit from the objective lens is changed to accommodate for the difference in focus for the different wave-lengths of light, the distance of the lens (L_1) must also be changed by an equal amount and in the same direction. This is accomplished by the micrometer adjustment described above. That is, the tubular sections which carry respectively the framework

for the slit and the holder for the lens are both operated by the same micrometer screw, hence any movement of the slit is accompanied by a similar movement of the lens. An adjustment of the distance of the lens for the slit, once made, need not, therefore, ever be disturbed in the process of accommodating for the difference in focus for the different wave-lengths of the spectrum.

In order that all stray light either from the general illumination of the room or by reflections from the Nernst glower be eliminated, the spectroscope and lens system are enclosed from just in front of the Nernst to the campimeter screen in a light-tight compartment. So far we have found it most convenient to make this compartment of light-proofed fabric. That is, the compartment must be made large enough to enclose all of the auxiliary reduction and adjusting apparatus, the thermopile, etc., and must permit of easy entrance for the purpose of making the adjustments and settings required. The construction of a compartment having these requirements we found could be most simply and feasibly accomplished by employing, as stated above, light-proofed fabric. There are so many ways in which such a compartment can be constructed that space will not be taken here for a description of the compartment we have used. It will be sufficient to say that adequate care has been taken to exclude any stray light that might find its way into the stimulus by means of reflections and refractions within the system.

It is well known to spectroscopists that if some portion of the spectrum obtained by a single spectroscope be examined by a second instrument of good resolving power, frequently more than one band will be obtained. For example, if a spectroscope is so adjusted that only a narrow region of the red falls on the objective slit and the light emerging from this slit is passed through a second spectroscope, it may be found that the second resolution gives one or more comparatively faint bands in some other part of the spectrum. In most cases where a good instrument is used this degree of impurity would probably not appreciably change either the radiometric or optical results. However, we have endeavored to

devise means whereby light of such a degree of purity may be obtained that the second resolution shows only the one band. Our first step in this direction was (*a*) to eliminate as far as possible all stray light and internal reflections. Stray light was eliminated by carefully light-proofing the housing of the apparatus. Also the base of the prism and every other surface which might either admit or reflect extraneous light into the path of the refracted beam was blacked. Some of the harmful sources of internal reflection were found to be the bounding surfaces of the objective lens, the prism faces and the analyzing slit, principally the surfaces of the lens.[1] For example, in looking into the forward end of the objective tube a number of small images of the spectrum can be seen graded in size and nearly in line but projected to different distances. These images show of course that light is being reflected back and forth in the optical system. The amount of this reflection can be lessened to a considerable extent by reducing the area (cutting out the edges) of the lens and prism surface exposed to the beam of light. However, since this method of reducing the amount of internal reflection lessens also the intensity of light, only a limited use was made of it. If care is not taken to prevent it, light from neighboring regions of the spectrum will also be reflected back into the objective tube from the surfaces on either side of the analyzing slit. These surfaces should, therefore, be very carefully blacked. Some good perhaps is accomplished by slanting them slightly so that the edges of the slit point in the direction from which the light is coming. The effect of this is to reflect out of the system all light but that which passes through the slit. The edges of the slit also require careful attention if reflections are to be avoided. The knife-edge should not be obtained by a steeply pitched bevel on either side. We have found that very satisfactory edges may be made from sections of Gillette razor blades. (*b*) A minimum deviation device was attached to our spectroscope (see pp. 258–260). This was found to add a great deal to the

[1] The surfaces of this lens being concave on the side opposite to which the light enters the lens tend to reflect the parallel waves toward the axis of the beam, and thus again to mix the light which had been resolved by the prism.

purity of the spectrum.[1] But (*c*) the simplest and most effective device proved to be the use of thin gelatine filters especially selected with reference to the bands that were to be eliminated. The use of these filters in fact is enough to give the desired purity even when no other precautions are taken. Moreover, we were able to select these filters so that there was so little absorption of the light that we wished to use as to be of no consequence for the purposes of our work. They were mounted in an especially constructed holder between the objective tube of the spectroscope and the analyzing slit. A similar result could be accomplished by using two spectroscopes in series.[1] But the expense and inconvenience of doing this make it undesirable in work of the type we are doing, more especially when the desired purity can be obtained by the simple means described above with probably a negligible reduction of the intensity of the useful light.

Apparatus for Varying the Intensity of the Stimulus Light

In designing an apparatus which will be at all broadly serviceable in the investigation of color sensitivity, due

[1] Our attention was called to the effect of the minimum deviation by the observation that when the prism was adjusted for minimum deviation for the D-line and the wave-length was changed by shifting the spectroscope by means of the driving screw shown in Fig. 2, the farther the D-line was from the analyzing-slit, the greater were the number of bands which appeared in the field when the light emerging from the slit was examined by means of a second spectroscope. Without the use of the gelatines or a second spectroscope, however, we have not been able to get rid entirely of the bands mentioned above.

[1] It is obvious that an advantage is gained here for purity over and above the increase in resolving power given by two prisms. Increase in resolving power is usually gotten by using a train of prisms in a single spectroscope or a single prism through which the light is passed more than once. (The Cassie prism used earlier in our work is of this latter type, see this paper, footnote, p. 260.) But while increasing the resolving power increases the purity of the spectrum (Schuster, 'Theory of Optics,' p. 163 expresses the dependence of purity on resolving power by the formula $P = pR$, where P represents purity; R, resolving power; and p, a factor which is a function of the slit-width), the impurities caused by internal reflections are clearly of a kind that can never be eliminated entirely by an increase of the resolving power of the prism or train of prisms. This, so far as we know, can be done only in ways similar to those described above. The use of a second spectroscope, however, besides being much more expensive and more inconvenient to manipulate, causes a greater decrease

attention should be paid to adequate means of varying intensity. This has become of especial importance because of the growing recognition of the usefulness of the threshold and just noticeable difference determinations as the basis of comparative work. We have designed, therefore, apparatus to produce both gross and fine changes in the amount of light employed, more especially the small gradations

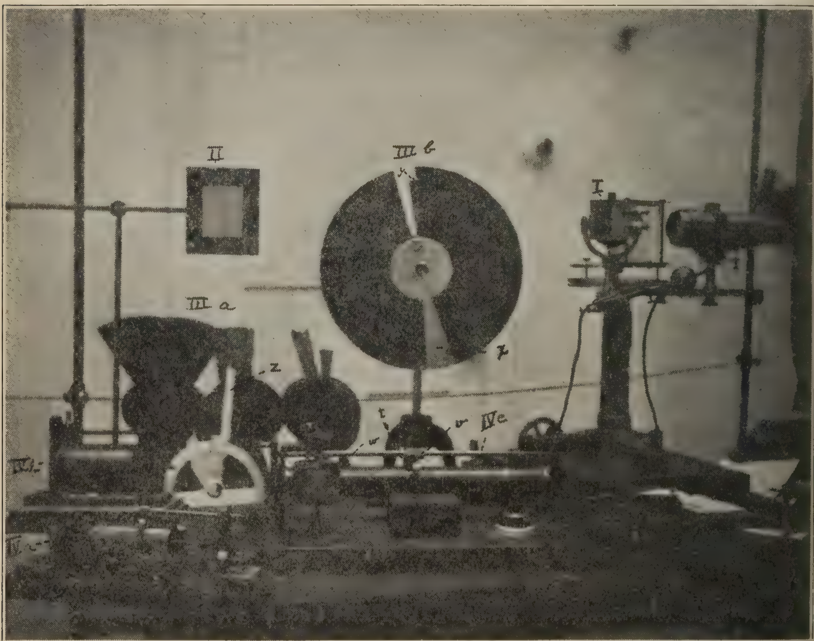

FIG. 5. Showing Auxiliary Apparatus Designed for the Reduction of the Intensity of Light—specially constructed resistance coils, coarse grating, aluminum sectored discs with Vernier protractor, and collimator slits including just noticeable difference slit.[1]

needed for threshold and just noticeable difference determinations. This apparatus is shown in Fig. 5. It consists

in the intensity of light used as stimulus than do the filters mentioned above, which when properly selected may produce practically no change in a given region of the spectrum and absorb heavily in other regions.

[1] In III. *b* the disc made up of a single 15° sector (*x*) is shown bright side before to make it distinguishable from the remainder of the compounded disc. When in use it is placed behind the other discs and the black side is turned towards the focusing lens just behind the stimulus-opening.

of (1) two types of collimator slit, one of which is especially devised for just noticeable difference work; (2) coarse gratings designed to give gross variations in the intensity of light; (3) sectored discs suitable for threshold and just noticeable difference work in which all of the changes from 0°–348.75° total aperture may be made, and a protractor with Vernier scale to permit of close reading of the discs especially when the aperture is small; and (4) special resistance coils designed to vary the intensity of light at the source.

Collimator Slits.—One of these slits is of the usual type having carefully beveled knife-edged jaws 12 mm. long, with a micrometer adjustment of width graduated to thousandths of a mm. Such a slit may be used (*a*) to make a reduction of the spectrum as a whole or of any part, and the reduction may be computed directly from the slit width provided the source is uniformly luminous over the surface exposed; or (*b*) one part of the spectrum may be made in turn to sustain, within limits and under the conditions mentioned above, any ratio that may be desired to any other part of the spectrum, providing the original intensities from which the reductions are made, are known. This slit, however, is not adapted to just noticeable difference determinations for a given color or range of wave-lengths. The second slit (shown at *I*, Fig. 5) is especially designed for just noticeable difference work. This slit is constructed so that its upper and lower halves are independently variable in width. It was designed especially for some new methods we are using for a quantitative comparative determination of the retina's inertia to the different wave-lengths of light in which just noticeable differences are employed. In the short exposures used in tracing the sensation from the threshold to its maximum, it is obvious that the sectored disc could not be employed in making the variations needed for just noticeable differences. While designed to meet this special need we have found it to be a very convenient means of making the variations needed for much of the general work in just noticeable difference determinations. The slit is formed by three knife-edged jaws. That is, one jaw of the slit is made

in one piece and is 12 mm. long; the other jaw is made in two pieces, each 6 mm. long. One edge, the upper for the upper jaw and the lower for the lower jaw, is beveled to fit into a dovetailed guide cut in the frame. The other edge of each jaw is held in place by a slender close fitting key of appropriate length. The jaw, 12 mm. long, is stationary and the other two jaws are made to move away from it by two independent micrometer screws operated by drum heads graduated to thousandths of a millimeter. In operation the source is adjusted so that one edge of its equally luminous surface is flush with the stationary jaw and the other jaws are pulled away from it exposing as desired different widths of this surface. In a just noticeable difference series one half of the slit is held constant and the other is varied to give the just noticeable difference. When the width of slit needed for this is obtained, that half of the slit is held constant and the other is varied, and so on until the series is completed.

The Coarse Grating.—This device is serviceable for gross reductions of the spectrum as a whole. It is shown at II. in Figs. 5 and 2. The grating consists of an exposed photographic plate ruled on a dividing engine with lines 60 to the centimeter. The gelatine side of the plate is covered with a thin glass plate and the whole is mounted in a brass frame supported by a slender rod running parallel to the lines of the grating. This rod fits into a collar furnished with a set screw so that the grating may be rotated any amount that is desired about the axis of the rod. When interposed in the path of the light this grating allows the maximum amount of light to pass through when it is perpendicular to the path. As it is rotated, less and less light gets through the open spaces afforded by the lines, the amount depending upon the angle of rotation. If it were wanted to use this grating as a more precise instrument of reduction, it would be comparatively simple to add a graduated scale so that any previous setting might be reproduced, and to calibrate the scale so that the amount of reduction might be read directly from it. So far in our work we have not felt the need to do this as the grating has been used only in making gross reductions in the amount

of light employed, the finer changes being made either by the slit or by the sectored discs. This grating may be mounted anywhere in the path of the light from the source to the campimeter screen. Thus far we have found it most convenient to insert it between the collimator and the prism (see Fig. 2).

The Sectored Discs and Vernier Protractor.—Probably the most convenient and widely applicable apparatus for varying the intensity of light by known amounts is the sectored disc. A strong objection to the use of the sectored disc when fine changes are needed such as are required, for example, in threshold and just noticeable difference work, is the difficulty of getting and of measuring accurately sufficiently small amounts of change. Such discs are ordinarily constructed with two or more open sectors, and a change in one is multiplied as many times as there are open sectors. Moreover, an error made in the measurement of one sector is multiplied by the number of open sectors. This latter difficulty becomes especially significant in working with intensities at or near the threshold when a small error may represent a high percentage of the total open sector. We have sought to overcome these difficulties in two ways. (1) Our discs for a low total aperture are so constructed that one sector may be varied at a time. And (2) a special protractor has been designed fitted with a movable arm carrying a knife edge and Vernier scale graduated to read to 1/60 of a degree.

Two sets of discs were made in all—one for simple reductions and threshold work, and the other for just noticeable difference determinations. The discs were cut from hard sheet aluminum No. 20 B. & S. gauge, 0.9 mm. thick; and are for the first set 19.5 cm. in radius. In order to give a wide range of change a number of discs are required. For example, a variation of total range of open sector from 0°–348.75° is obtained in the first set of discs by using four pairs of two-sector discs and one pair of one-sector discs with a counter-balancing weight. In the first pair the breadth of each of the two open sectors is 90°, and the range of variation

of total open sector is from 0°–180°; in the second pair the breadth of each of the two sectors is 45° and the range of variation of total open aperture is from 180°–270°; in the third pair the breadth of each of the two open sectors is 22.5° and the range of total aperture is 270°–315°; in the fourth pair the breadth of each of the two sectors is 11.25° and the range of total aperture is 315°–337.5°; and in the fifth pair the breadth of the single sector is 11.25° and the range of total aperture is from 337.5°–348.75°. In order that very small apertures may be obtained or that small variations of aperture may be had, when each open sector is 15° or less, a small single sector furnished with counter-balancing weight was provided in addition to the five pairs of discs. When this is used with the pair of discs having 90° sectors to cover one of the open sectors, the total aperture may be varied from 0° through 15°. This single sector may also be used in connection with any of the other pairs of discs to aid in making smaller variations in the total aperture than is obtainable with the pair of discs alone. That is, as one of the open sectors is opened, the other may be closed by any desired amount less than 15° by means of this single sector. Following this principle broader single sectors may be constructed to permit of smaller variations when the total aperture is still larger. We have found, however, that the 15° sector satisfies the need for the values of total aperture for which small changes are significant.[1]

In order to make the first set of discs serve also for just noticeable difference determinations, it was necessary to supplement each of the pairs of discs in this set with single discs of the same breadth of sector and of lesser radius.

[1] In the construction of these discs a solid disc with a radius of 19.5 cm. was first cut from a sheet of aluminum. The open sectors were then cut into these discs of the breadth desired to a depth of 13.5 cm. This left a small solid disc of 6 cm. radius to support the pairs of sectors. As was stated above in order to guarantee symmetry of rotation in case of the single sectors, a counterbalancing weight was fastened on the opposite side from the sector 6 cm. from the center of rotation. This weight was in the form of a small lead disc soldered to the inside supporting disc in line with the radius which just bisects the sector. It is scarcely needful to say that great accuracy is demanded in the cutting of the discs. This accuracy was obtained by means of a special cutter designed for cutting with accuracy straight and curved edges in metal.

These discs were 17 cm. in radius and the open sectors were cut in from the outer edge to a depth of 11 cm. A margin of 2.5 cm. was thus left between the edges of the two sets of discs. In making the just noticeable difference determination the two sets of discs are adjusted so that the edge of the inner disc just bisects the stimulus-opening. The openings of the two sets are then varied independently as may be required, it being necessary of course always to make the open sectors of the outer discs the larger. The sectored discs are shown at III. *a* in Fig. 5. The method of using them is further illustrated at III. *b*. Here the discs are shown mounted on an electric color mixer and are set for a just noticeable difference determination low in the intensity scale. Two of the set of larger discs each having two 90° sectors are mounted to give two open sectors one of which is closed by means of the single 15° sector shown at *x*, leaving a total aperture of 10°. In front of these is mounted the disc of smaller radius with the edge of one of its sectors shown at *y* projecting 4° into the 10° opening reducing it to 6°. When the disc so compounded is adjusted in front of the stimulus-opening so that the edge of the disc of shorter radius just bisects this opening and the disc is rotated at the fusion rate, the two halves of the opening are illuminated with light of intensities proportional respectively to 10 and 6. By using the discs of different breadths of sector, similar variations can be achieved over a range 0°–347.75° open sector.

The special protractor by means of which the width of the open sectors may be read to 1/60 of a degree is shown at Z. This protractor is provided with a 180° arc of 10 cm. inside radius, and an arm 27 cm. long which rotates about a central collar closely fitting the chuck of the motor. The 180° arc is graduated to 1/4 degrees and the movable arm carries a Vernier scale graduated to 1/60 degrees. The movable arm carries a beveled slot also of a 10 cm. radius of curvature into which the 180° arc fits. To insure accuracy of setting this movable arm is provided with finely beveled straight edges. When making a measurement of open sector, one of these edges is set flush with one of the edges of the sector

and the reading made. It is then rotated until the same edge is flush with the other edge of the sector, and the difference between the readings is taken as the value of the sector. We have thought it necessary to stress the accuracy with which these measurements must be made because the threshold value of sensation is frequently obtained for the intensities of light employed by us with a total aperture of 1/15°. With such small apertures it is obvious that accuracy of measurement becomes of prime importance. When used in connection with the spectroscopic apparatus described in a preceding section to determine the threshold and just noticeable differences in sensation, the sectored discs are interposed in the path of the parallel beam of light just behind the lens L_2 (see Figs. 2 and 3). As is shown in this figure in order to eliminate as far as possible all vibrations and consequent displacements of the edges of the discs from the desired alignment with the beam of light, the discs are mounted on a motor (*S*) suspended by springs. With discs so designed and used, and with the proper standardization of the factors which influence the response of the eye, determinations may be made having a very high degree of reproducibility.

Special Resistance Coils.—Special resistance coils have been devised which serve the following purposes: (1) to give the fine changes of resistance needed to compensate for fluctuations of voltage in the lighting circuit which otherwise might produce troublesome variations in the flux of light from the Nernst filament; (2) to produce changes in the intensity of the spectrum given by the filament;[1] and (3) to make possible the fine changes in the speed of rotation of the discs that are so frequently required in work in the optics of color. These coils are of two general types. (*a*) Coils which give fine changes over a narrow range; and (*b*) coils which will permit of fine changes over a wide range. Coils of the first type are shown in Fig. 5 at IV. *a* and *b*; a coil of the second type at IV. *c*. The resistances of the first type consist of one coil and are constructed to give the effect of a

[1] It was recognized of course in using the resistance for this purpose that a change in the amount of current by which the Nernst is operated changes the spectro-radiometric composition of the light.

contact sliding along a single wire. The effect is produced by winding the coil of wire of the desired size and resistance on a hollow brass cylinder insulated with micanite, and by turning this coil by means of a screw motion under a U-shaped contact. In this way the contact is made to travel along the entire length of the wire, and the fineness of change is limited only by the size and coefficient of resistance of the wire. In one example of this general type of resistance shown in Fig. 5 (IV. *a*), the contact is kept stationary and the cylinder is mounted on a rod as its axis, threaded at both ends. As this rod operated by a milled head turns, the cylinder rotates and slowly advances, so that the contact travels continuously over the whole length of the wire. In a second example of this type, shown at IV. *b*, the contact slowly advances as the cylinder is rotated, and passes continuously over the whole length of the wire. This effect is accomplished as follows. The cylinder is mounted on a horizontal rod turned by a geared wheel 5 cm. in diameter. The contact is mounted on a threaded rod which is turned by a geared wheel of the same diameter as the wheel which turns the cylinder As the latter wheel turns, its teeth engage the teeth of the wheel which rotates the rod on which the anchor piece of the contact is threaded, and the contact advances along the rod at a rate which keeps it continuously in touch with the wire throughout its whole length. The coil which we use to control the amount of current operating the Nernst filament is made of No. 26 wire, 47.8 ft. long, and has a resistance of 55 ohms.

The resistance of the second general type consists of two coils in series, one designed to make gross changes and one to add fine changes to it for any given setting of the contact. The wire of the first coil is wound on a long section of brass tubing insulated by micanite. This tube was given a stationary mounting and the changes in resistance are produced by a sliding contact shown at *v*. The supplementary coil was wound on a brass drum shown at *w*, insulated by micanite and mounted on a vertical threaded rod operated by a small wheel. As this wheel is turned the drum rotates and

slowly changes its level bringing every point on the wire successively in touch with a stationary contact. The connections are so made in this rheostat that by means of a double-pole switch shown at *t*, the poles of the large coil can be reversed and a high rate of speed can be instantly changed to a low rate of speed, and *vice versa*. In the rheostat shown in Fig. 5, the large coil is made of Advance wire No. 26, 139 ft. long, and has a resistance of 160 ohms. The small supplementary coil is made of wire of the same composition, No. 26, 17.4 ft. long, and has a resistance of 20 ohms. By means of these two coils changes of resistance amounting to very small fractions of an ohm can be made and the speed of rotation of motors of the type constructed by the C. H. Stoelting Co., for example, can be controlled to fractions of a revolution per second. We have found such control to be very useful in the general field of work in which impressions are to be g ven to the eye in succession, and especially necessary in the studies that we have made of the factors that influence the results obtained by the method of flicker for the photometry of lights of different color. It is obvious that some such control must be had if the phenomena produced by changing the rate at which impressions are given to the eye are to be studied in satisfactory detail.

The Rotary Campimeter

In a previous paper[1] a rotary campimeter was described especially devised for use with pigment papers. At that time it was stated that this apparatus had also been adapted for use with a spectroscope, and that a description of it would be given in a later paper. The apparatus we shall here describe has been in use, therefore, for three years and its feasibility has been tested for that length of time both in the research and drill work of the laboratory.

The object of the rotary campimeter is to add to the vertical campimeter the rotary features of the perimeter, and thus to allow investigation of every possible meridian of the retina

[1] C. E. Ferree, 'Description of a Rotary Campimeter,' *American Jour. of Psychol.*, 1912, *23*, pp. 449–453.

with as much ease and precision as was possible with the old form of campimeter in the nasal meridian only, or at most in the nasal and temporal meridians. As designed for use with the spectroscope this apparatus consists of two parts with appropriate supports and accessories: campimeter screen and lens to focus the light on the pupil of the eye and to shift the image to follow the pupil as it takes an excentric fixation; and attachment to line up the eye with the stimulus-opening. The campimeter screen rotates on a brass collar around a circular support. The stimulus is exposed through an opening in the center of the campimeter screen. Behind this opening mounted in a smaller brass collar is the focusing lens (L_2). This lens is carried on a rack and pinion which moves its center back and forth along a line which passes through the center of the stimulus opening and which contains all the fixation points on the arm (I–I').

Fig. 6 shows the skeleton apparatus. It consists of the following parts: supporting base, frame for campimeter screen,

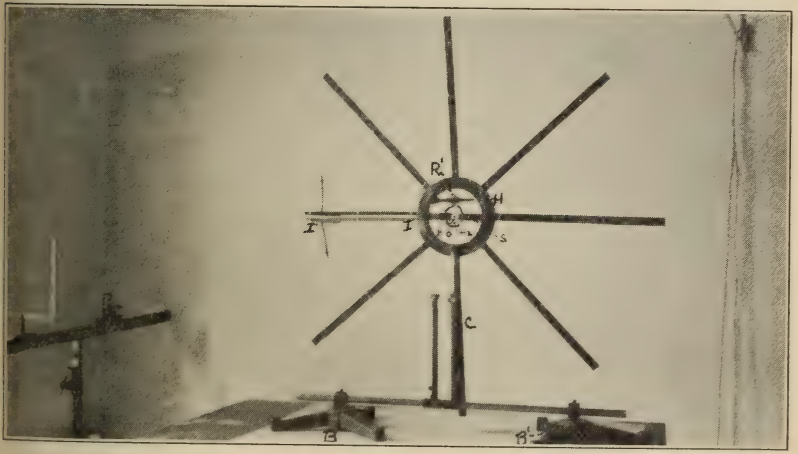

Fig. 6. Showing the Rotary Campimeter, the Lens for Focusing the Light on the Eye, and the Rack and Pinion used to shift the focal point as the eye changes its fixation.

rack and pinion adjustment and support for the focusing lens, and attachment for lining up the eye with the stimulus-opening. The supporting base consists of a horizontal steel

bar, 83 cm. long, supported by two tripod rests (B and B'). To this bar is clamped an upright (c) which serves as a support for the framework of the campimeter screen. In order that the distance of the upright of the screen above the table may be adjustable, this upright consists of a steel tube 27 cm. long and 15 cm. in diameter furnished at its upper end with a collar and set screw into which fits a rod 20 cm. long, to which the framework of the campimeter screen is attached. The framework of the campimeter screen consists of a stationary brass ring about which rotates a larger brass collar (H), 20 cm. in diameter.[1]

The back circumference of collar (H) is graduated from 0°–360°. To this collar are fastened the radiating arms. There are eight of these arms, one for each 45° mark on the graduated collar. They are made of steel and are 2 cm. broad and 40 cm. long. The eighth arm (I–I') differs from the other seven. It forms a right angle, one side of which lies in the plane of the background, and the other in front of this plane. The part in the plane of the background is 60 cm. long and the part at right angles to this plane is 28 cm. long. The arm is graduated from 18°–57° along the section that lies in the plane of the background, and from 57°–92° along the section at right angles. The graduations are based on the arc of a circle of 25 cm. radius. The rack and pinion adjustment (R') which carries the focusing lens is attached to the rotating collar. Thus when the arm carrying the fixation points is rotated into any given meridian, the rack and pinion adjustment is also rotated so that the line of motion of the center of the lens always contains the fixation points. The focusing lens (L_2) is a double convex lens 50

[1] This ring was made large in diameter for two reasons. (a) The ring had to be made thick in order to give sufficient rigidity to support the campimeter screen and to furnish the proper attachment for the rotary collar. Had the circumferance been made small, the effect of the ring would have been that of a short tube. If the stimulus were viewed through a short tube, an induction factor would have been involved which would have been difficult if not impossible to standardize. The opening of the ring was, therefore, made considerably larger than any stimulus we wished to use in order to avoid the introduction of this factor. (b) The large circumference of the ring makes the apparatus available for investigating the effect upon sensitivity of varying the size of the stimulus.

mm. in diameter and with a focal length of 275 mm. It moves in a plane 2.5 cm. behind the stimulus-opening, hence the parallel rays of light entering it from the collimating lens (L_1) are brought to a focus on the pupil of the eye when in position 25 cm. behind the stimulus-opening. To the eye at this point, the lens, or as much of it as is visible through the stimulus-opening, is seen uniformly filled with light. That is, it is a well-known fact in physiological optics that when parallel rays of light are focused on the pupil of the eye, or more accurately perhaps, at the optic center of the refracting mechanism, by means of a double convex lens, the lens is seen by the eye as if uniformly filled with light. As the eye takes the different fixation points on the arm (I–I') the light is kept focused on the pupil by slightly displacing by means of the rack and pinion adjustment the center of the lens in the direction in which the eye is turned in taking the new fixation.[1] The adjustment is quickly and easily made. In fact the rotary campimeter adapted to the spectroscope in the manner described in this paper presents little if any more difficulty of operation than it does when pigment papers are used as stimuli.

The device for lining up the eye with the stimulus-opening is also attached to the rotary collar (H) and is constructed as follows. A cross piece (S) 16 cm. long and 1.8 cm. wide is fastened by a screw with a milled head to one side of the collar (H) and is supported by a pin on the opposite side. A pin is used instead of a second fastening in order that the device may be conveniently and quickly turned out of the path of light when not in use. In the center of the cross piece (S) is a circular opening (O) 15 mm. wide. When in position immediately behind the opening in the campimeter screen which admits the stimulus light, the center of this opening lies in a line perpendicular to the opening in the screen at its central point. To the cross piece (S) 3 cm. to

[1] In taking a new fixation the pupil is seen to turn from under the colored image and to the observer the stimulus-opening is no longer filled with colored light. As the center of the lens is shifted in the appropriate direction, however, the image is seen to travel towards the pupil, and when it falls full upon it, the observer again sees the stimulus-opening filled with light.

the side of the opening (*O*) is fastened at right angles an arm 12 cm. long and 1 cm. wide, terminating in a disc (*P*) 2 cm. in diameter. Three centimeters from its outer end this arm is bent at right angles so that the disc lies directly behind the opening (*O*) and in a plane parallel to that opening. The size and position of the stimulus-opening, the opening (*O*), and the disc (*P*), and their distances from each other sustain such relations that when the eye is in position 25 cm. behind the stimulus-opening with the center of the image of that opening on the fovea and the line of regard normal to the plane of the opening, the edge of the opening (*O*) is just contained within the stimulus-opening and the edge of the disc is just contained within the opening *O*. That is, in effect the device is a peep sight arrangement, and the alignment described above is possible only when the eye is at the center of curvature from which the fixation points on the arm (*I–I′*) are determined. As stated above, this attachment is fastened to the collar (*H*) by means of a screw with a milled head, so that after the alignment is made it can be readily turned out of the road and clamped. In order that the distance of the eye may be adjusted at the same time as its alignment is made with the stimulus-opening, a measuring device 25 cm. long is provided. This device consists of a slender brass rod fitted at either end with two short right angled arms 5 mm. in length. On the end of one of these arms is a ring which is just larger than the stimulus-opening, and on the other is a brass disc of the same diameter as the ring, provided at its center with a pupillary aperture. In adjusting the distance of the eye the disc is rested lightly against the forward surface of the eyeball and the ring against the campimeter screen concentric with the stimulus-opening. When the position of the eye is once determined, a mouthboard is adjusted and clamped in position so that the observer's teeth fit into impressions previously made and hardened in wax. This fixes the relation of the observer's eye to the campimeter system. All that is needed, therefore, at subsequent sittings to bring the eye into this relation is again to fit the teeth into the impressions on the mouthboard.

In order to facilitate excentric fixation in the nasal and temporal meridians, the head should be turned in adjusting the mouthboard 45° nasalwards or temporalwards as the case may be. With the head so placed, the eye can swing easily from the stimulus-opening to a fixation point whose excentricity exceeds 90°.

The front view of the campimeter in readiness for use may be seen in Fig. 2 of our former paper; a back view is given in Fig. 3 of this paper. A cardboard background has been fastened to the steel arms by means of metal fasteners pushed through holes in the steel arms and clinched. Since the background is fastened to the arms attached to the brass collar (*H*), a circular gap is left at its center. This gap is filled by a disc (*N*) shown in Fig. 3, which has been fastened to the arms just outside of the collar (*H*). The disc is 27 cm. in diameter and contains the stimulus-opening (*O*), the size of which may be varied to accord with the purpose of the investigation. In order to complete the graduations on the fixation arm to the stimulus-opening, disc (*N*) is graduated from 0°–18°. A background, 40 cm. in height, is fastened to the extension arms (*I′*). This background for screen and extension arm may be covered with whatever standard paper or surface that is desired.[1] The graduations from 0°–92° are pricked in this covering at points determined by the markings on the back of the disc (*N*) and the arm (*I–I′*). These constitute the fixation points.

The method of using this apparatus is as follows. The eye of the observer is lined up with the stimulus-opening by means of the attachment described above at a point 25 cm. from the campimeter screen; and the position of his mouthboard is adjusted. With his eye in this position the lens should fill uniformly with light whenever the image of the analyzing slit falls on the pupil. Before the color observations are begun this is tested out by taking a number of

[1] In all tests of the relative and absolute sensitivity of the retina this screen should be made of a gray of the brightness of the color to be used. No departure from this rule should be permitted in tests of sensitivity unless it is for the purpose of determining the effect of different screens on sensitivity, or of using this effect as a means of varying sensitivity.

fixation points from 0° to the periphery of the field of vision and adjusting the focusing lens in each case to bring the image of the slit full upon the pupil of the eye. In making the color observation the unused eye is covered with a bandage. The arm (*I–I′*) is turned into the meridian to be investigated, the position being determined by the graduations on the collar (*H*). The experimenter inserts a card which we shall call the preëxposure card, between the eye and the stimulus-opening as near to the opening as possible while the observer takes the fixation required. In all investigations of relative and absolute sensitivity, this card should be made of a gray of the brightness of the color to be used. At a signal given by the observer the preëxposure card is withdrawn, the eye is exposed to the stimulus for the required length of time and the card is replaced in the path of the stimulus light. The observer is required to rest the eye after each observation. Further provisions against fatigue are made by frequent and regular intervals of rest.

It is often desirable to have an equation representing what is sensed at a given point in the peripheral retina in terms of what is sensed in the central retina. In this way a representation may be had for comparative purposes of the color tone, brightness and saturation for light of a given intensity and range of wave-length.[1] In the campimeter devised for use with pigment papers provisions were made for this. That is, it was possible to rotate a small disc on which the representation might be made, just behind the fixation point for all positions of the point from 0°–90° in any meridian. This disc was rotated by a small motor the shank of which protruded through a slit 8 mm. wide running the full length of the fixation arm (*I–I′*). For a further description of this motor, its supports, adjustments, etc., and the method of making the match of the sensations aroused in central and peripheral retina, see the former

[1] In making a comparative study of the sensitivity of the different parts of the retina, such an investigation is a valuable supplement to a survey of sensitivity made on the basis of threshold and just noticeable difference determinations. The two methods are needed in fact to give a complete representation of the sensitivity of the retina in its quantitative and qualitative aspects.

article, p. 452. In the rotary campimeter devised for use with the light of the spectrum no similar provision has as yet been made. The difficulties appending the attempt to get a spectrum light variable at will in intensity, color, and brightness which can be easily and conveniently presented to the eye at any point of any meridian of the field of vision are obvious at a glance. Dreher, for example,[1] was able to make a match of the sensations aroused at the center and periphery of the retina without very inconvenient changes in his apparatus for one point only in the peripheral retina. An attempt is being made to adapt our present apparatus so that this match can be accomplished conveniently for any point in the peripheral retina, but as yet nothing definite can be promised.

[1] Dreher, *loc. cit.*

Bryn Mawr College Monographs

REPRINT SERIES, Vol. XII

Contributions from the Psychological Laboratory

BRYN MAWR, PENNA.

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MISCELLANEOUS EXPERIMENTS ON THE EFFICIENCY OF THE EYE UNDER DIFFERENT CONDITIONS OF LIGHTING.

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As one feature in the work of a preceding paper ("The Efficiency of the Eye Under Different Conditions of Lighting." (Ophthalmology, Vol. X, July, 1914, p. 622) we undertook to determine the most favorable intensities for the three types of lighting we had selected for investigation—direct, semi-indirect and indirect, and the effect of varying intensity with the particular grouping of distribution factors* represented in each case. This work was completed for the direct and semi-indirect systems, but not for the indirect. In the present paper results will be given for a similar series of experiments pertaining somewhat more broadly to the hygienic employment of the eye.

The tests are made in the same room, with the same fixtures, and in general with the same conditions of installation and methods of working as were employed in the work of the preceding paper. To secure the various degrees of intensity needed, tungsten lamps of different wattages were used. The series began with 25-watt lamps and included 25, 40, 60 and 100-watt lamps. The results of these experiments are given in Chart 1. In this chart are also included for the sake of comparison graphic representations of the results obtained by a similar variation of intensity for the direct and semi-indirect systems. In drawing conclusions from these results the effects on the eye should of course be correlated with the illumination effects produced. For a full specification of these effects, also those treated in the next paragraph, see Transactions of the Illuminating Engineering Society, 1915, X, pp.

*The distribution factors are evenness of illumination, evenness of surface brightness, diffuseness of light and angle at which the light falls on the work.

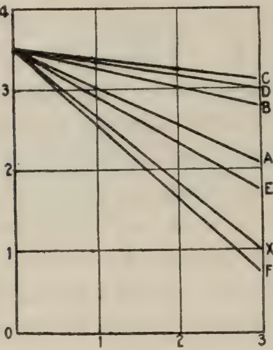
(REPRINTED FROM OPHTHALMOLOGY, JULY, 1916)

CHART I.—INTENSITY SERIES.

Showing a comparison of the effect on visual efficiency or power t sustain clear seeing of varying the intensity of light for the four in stallations of lighting used: the indirect, semi-indirect and direct sys tems, 8 lamps; and the direct system, 16 lamps.[1]

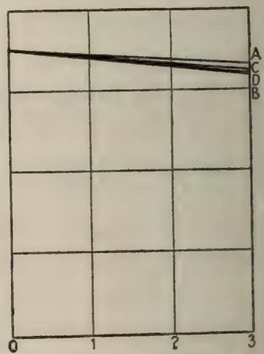
Lighting system: Semi-indirect

	Watts	Volts	Foot-candles Horizontal	Vertical	45°
A	200	107	1.6	0.45	1.15
B	200	110	1.72	0.484	1.29
C	320	107	2.2	0.58	1.52
D	320	110	2.31	0.62	1.61
E	480	107	3.3	0.94	2.4
F	800	107	6.8	1.82	4.5
X	760	107	5.8	1.45	4.0



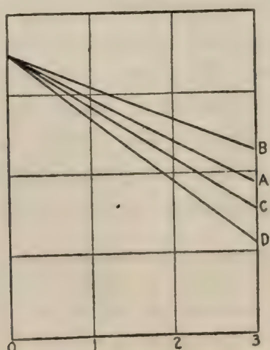
Lighting system: Indirect

	Watts	Volts	Foot-candles Horizontal	Vertical	45°
A	200	107	1.33	0.39	0.87
B	320	107	1.7	0.49	1.0
C	480	107	3.0	0.765	1.9
D	800	107	5.2	1.36	3.5



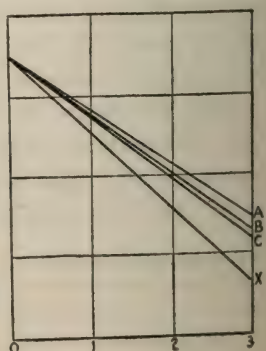
Lighting system: Direct (8 lamps)

	Watts	Volts	Foot-candles Horizontal	Vertical	45°
A	120	107	0.64	0.32	0.49
B	200	107	1.16	0.45	0.85
C	320	107	1.97	0.65	1.39
D	480	107	2.6	1.02	2.0



Lighting system: Direct (16 lam

	Watts	Volts	Foot-candles Horizontal	Vertical	45°
A	240	107	1.23	0.54	0.9
B	365	107	1.6	0.6	1.3
C	400	107	1.86	0.8	1.4
X	880	107	4.2	1.41	2.



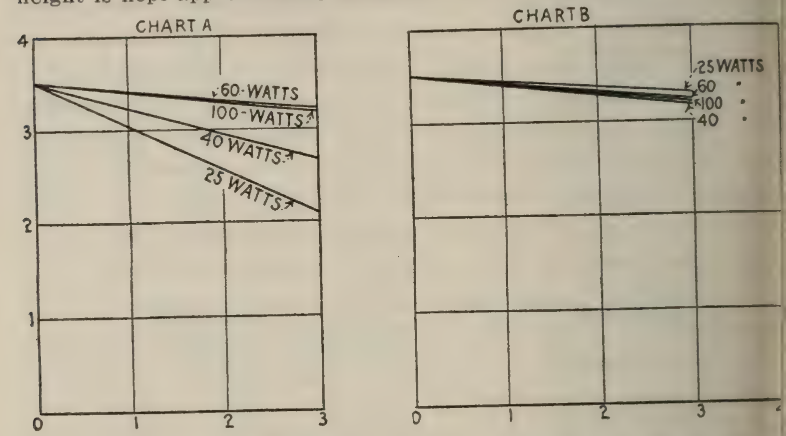
434-442 and 469-473. For the semi-indirect installation it will be seen that the eye fell off heavily in the power to sustain clear seeing for all intensities with the exception of a very narrow range on either side of 2.2 foot-candles measured at the point of work with the receiving test plate of the photometer in the horizontal plane. (In lighting practice 5 foot-candles is usually recommended as the value to be given to this component of illumination for ordinary work.) For the direct installation no intensity could be found for which the eye did not lose a great deal in power to sustain clear seeing as the result of work. For the indirect installation, however, it was found to be possible to use a comparatively wide range of intensities without causing the eye to suffer any considerable depression of functional power as measured by the test.

As was the case for the semi-indirect reflectors used in the work of the preceding paper, socket extenders had to be used with the 25 and 40-watt lamps. That is, without the extenders these lamps owing to their smaller size came so low in the reflector as to change the distribution effects given by the reflectors. For example, without the extenders for these shorter lamps, the spot of light on the ceiling was made smaller and correspondingly more brilliant. It was considered to be a point of interest in relation to the general problem to determine whether this comparatively small change in illumination would cause any difference in the eye's ability to hold its power to sustain clear seeing. A comparison of the results for the indirect reflectors with and without socket extenders is shown in Chart II.

Also in addition to the work on the distribution series reported in the previous paper it was decided to make a test of the effect on the eye of position in the room for the three systems of lighting for one of the intensities of light employed. Accordingly four representative positions in the median line of the room were selected: positions at which respectively six, four, two, and no lighting units were in the field of view. This variation of position at which the observation was made accomplishes two purposes. (1) It gives a more representative idea of the difference in the effect on the eye of the three types of lighting employed; and (2) it shows the effect of varying the number of surfaces in the field of view presenting brightness differences, more particularly the number of primary sources. As usual the intensity of light was as nearly as possible equal at the point of test for these installations, and a supplementary specification was given of the lighting effects in the remainder of the room (see Trans. I. E. S., 1915, X, pp. 414-

CHART II.—INTENSITY SERIES.

Showing the effect on loss of visual efficiency or power to sustain clear seeing of changing the height of the light source in the reflector of the indirect lighting fixtures. The effect on surface brightness is primarily to change the area and surface brilliancy of the spot of light thrown on the ceiling. Chart A shows the results when height of source in the reflector is changed; Chart B, the results when the height is kept approximately constant.

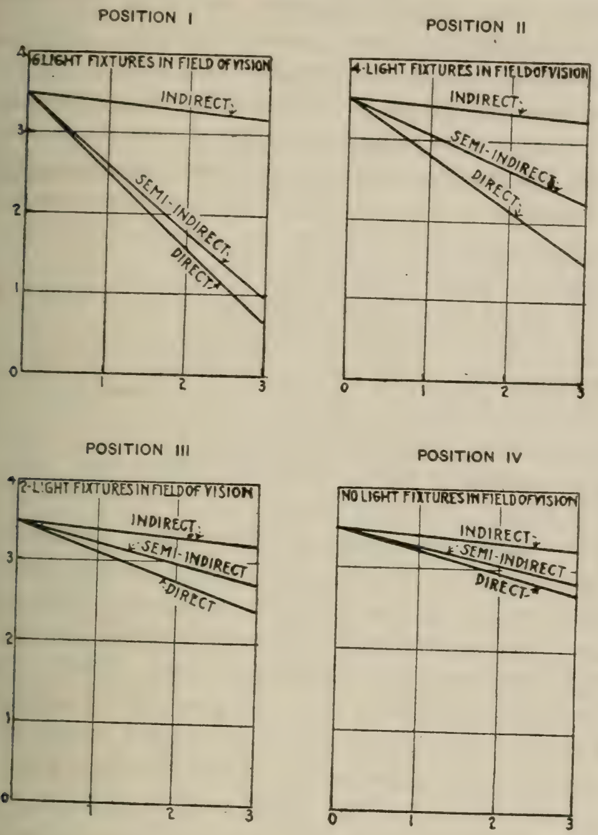


422 and 452-466). The lamps employed totaled 800 watts for th indirect system, 760 for the semi-indirect system, and 880 for th direct. An inspection of the tables of measurements referred t above shows in general a falling off in the magnitude of brightnes differences for all systems from Positions I-IV. This falling of however, is greatest for the direct system, next greatest for th semi-indirect system and least for the indirect. Thus there is nc only a decrease in the number of surfaces in the field of vie showing a high brilliancy from Positions I-IV, but also a decrea in the magnitude of brightness differences between the surfaces high brilliancy and the test card, between these surfaces and tl reading page, etc., especially for the direct and semi-indire systems. An inspection of the chart for loss of efficiency show roughly speaking, a correspondingly marked decrease in loss efficiency from Positions I-IV for the systems which show tl marked decrease in brightness differences, that is, for the dire and semi-indirect systems. The decrease in loss of efficiency is, will be noted, practically nothing for the indirect system. Th not only much less loss of efficiency is sustained by the eye for tl indirect units used, but the results are much more independe of the position of the observer in the room.

The comparative effects on the eye for the four positions in tl room are shown in Chart III.

CHART III.—DISTRIBUTION SERIES.

Showing the effect on loss of visual efficiency of varying the observer's position in the room, or the number of bright sources, primary and secondary, in the field of vision.



In constructing the above charts the figure expressing the ability to sustain clear seeing during the three-minute record before and after work is plotted along the ordinate and the hours of work along the abscissa. These two points are connected by a straight line the slope of which gives a graphic representation of the change in the power of the eye to sustain clear seeing from the beginning to the end of the three-hour period. During the working period the observer read steadily from uniform type and paper. In the selection and use of the observers for the work the following are some of the precautions that were taken. Care was exercised in the first place to choose only those that had already shown a satisfactory degree of precision in other work in physiological optics and whose clinic record showed no uncorrected defects of conse-

quence. All were under 30 years of age. Before being allowed to take part in the actual work of testing, each observer was trained to a satisfactory degree of precision for the three-minute acuity record under a given lighting condition and in the three-hour test for several of the conditions which were to be tested. In the actual work of testing the results were compiled from several observations and the precision checked up by the size of the mean variation. No results were accepted as significant unless the variations produced by changing the conditions to be tested were largely in excess of the mean variation or mean error for each condition tested. This the accepted conventional check on the influence of variable extraneous factors, was carefully applied at each step of the work.

In our choice of the first set of conditions to be tested, it will be remembered from our previous work that our purpose was to make a selection that would give a wide variation in illumination effects. The direct reflectors chosen were not of the most modern make, although they may be said to give effects very similar to much of the lighting in actual use at the present time. They were of porcelain ware 16 inches in diameter and only slightly concave. When placed above the lamps employed (clear tungsten) they served merely to distribute the light to the working plane. No protection from the brilliancy of the light source was afforded to the eye. For the semi-indirect system inverted alba reflectors, 11 inches in diameter, were employed. These reflectors were of modern design and represent very well glassware of medium density. In case of the indirect system corrugated mirror reflectors were used enclosed in brass bowls. These reflectors were also of modern design and give effects which may be taken to represent very well those obtained in good indirect lighting. In later papers results will be given for the smaller differences in illumination effects that may be obtained by using semi-indirect and direct reflectors differing in density and design. A large number of reflectors will be used chosen with special reference to their representative character by designers of both classes of reflectors. A great deal of this work has already been completed.

Eye Shade Series.

This series of experiments has been conducted for the following reasons: (1) In general two methods are used to protect the eye from the source of light, eye shades and lamp shades. It is desirable to know whether the eye is protected equally by both; and if the eye shade can be substituted for the lamp shade, what type of shade would best serve the purpose. (2) And the statement

been made to us many times that with an eye shade the three systems of artificial lighting we have used should give equally good results; and results, moreover, as good as those given by the indirect system without an eye shade. There are in general two classes of eye shades, the translucent and the opaque. Up to this time we have confined our work to the opaque shade. So far as we know, it is customary to make the opaque shade with a dark lining. This kind of lining is employed probably because of some notion that it is restful to the eye to darken as much of the field of vision as is possible.*

The tests were begun with the opaque shade with the dark lining. What we found as the result of these tests was somewhat in contradicition to the predictions that had been made. The shade did give pretty nearly the same results for the three systems, but it did this contrary to prediction by improving direct and semi-indirect systems and making worse, by an almost equal amount, the indirect system. That is, protected by the opaque shade the eye lost in efficiency for the three systems by an amount somewhere near the mean of the losses experienced by it for the three systems without a shade. Nor is this result surprising when one reflects upon the conditions imposed upon the eye by an opaque shade with a dark lining. While it protects the eye from the sources of light, such a shade does not by any means eliminate harmful brightness differences in the field of vision. It in fact creates for the eye a very unnatural brightness relation, i. e., it renders the whole upper half of the field of vision dark in sharp contrast with the brightly lighted lower half. The direct effect of this is a strong brightness induction (physiological) over the lower half of the field of vision which manifests itself to the observer by causing glare in surfaces which have no glare and by increasing the glare in surfaces in which glare is already present. This it is scarcely necessary to point out, operates against the discrimination of detail and puts the eye under strain to see its objects clearly. Moreover, the unusual and strongly irregular character of the image formed on the retina probably also sets up a warfare in the incentives given to the muscles which adjust the eye. That is, the upper half of the field of vision is dark and presents no detail. The effect of this is probably to exert a tendency to cause the muscular relaxation characteristic of f the darkened field of vision. The lower half of the field is light

*Another popular view might be, so far as protection to the eye is concerned, to regard the opaque shade as the analogue of the opaque or perhaps the indirect reflector and the translucent shade as the analogue of semi-indirect reflector.

and filled with detail. The incentive here is towards the best possible adjustment of the eye for the discrimination of detail in the object, while the rim of the shade, the sharply marked boundary between the dark and light halves of the field of vision and much nearer to the eye than the objects viewed,* serves as a constant and consciously annoying distraction to fixation and accommodation. These complex and somewhat contradictory impulses giver to the muscles of the eye might very well and doubtless do caus an excessive and unnatural loss of energy and efficiency in cas of the prolonged adjustment of the eye needed for a period of work

Early in the course of the tests it occurred to us that we migh render the brightness distribution in the field of view presented t the eye wearing a shade, more natural and thereby improve th effect of the shade on the eye, by employing a white instead of dark lining. By using a mat white paper* with a reflection coef ficient of about 75 per cent. for this lining, the following effect were produced. The two halves of the field of vision were ren ered much more nearly of equal brightness; the glare in the low half of the field of vision was very noticeably lessened and the di crimination of detail was correspondingly improved; the upper ha of the field of view no longer tended to give to the eye the reflex of the darkened field of vision; and the rim of the shade did n stand out nearly so distinctly in the field of view to distract accom modation and fixation. That is, the whole lining of the shade wa darkened just enough by being shielded from the light of t room by the shade itself to make it nearly equal in brightness the rest of the field of vision. The effect of this was to make t shade merge into the field of view rather than to stand out d tinctly from it. A shade to give the best effects should be se as little as possible. It thus offers a minimum of distraction o the proper adjustment of the eye for its work.

The results of the test for loss of efficiency show, moreover (Se Chart IV), that our surmise with regard to the effect on the e of this change in the lining of the shade was correct. The actn of the white lining was greatly to improve the ability of the e to maintain its efficiency for a period of work. As good resu were not gotten, however, with the shade for any of the syste as were given by the indirect system without the shade. Si there was a still greater evenness of surface brightness in the fi

*This rim is about three inches in front of the observer's eye wh the shade is in position.

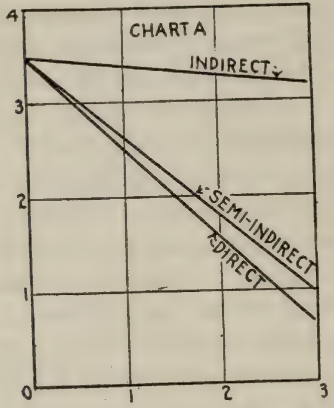
*Hering standard white paper was used for this lining. The reflec coefficient of the dark lining was about 6-8 per cent.

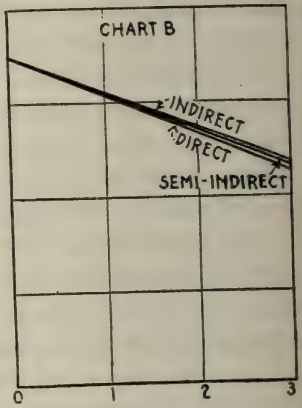
of view in case of the indirect system with the eye shade than without, the question arises why at least as good results were not obtained with the shade as without. The answer, we believe, is to be found in terms of the distraction to fixation and accommodation caused by the eye shade even when a light lining was used. For the effect of a shade on the eye even when the most favorable lining is employed is that of a constantly present distracting object with its lower margin not far removed from the center of the field of vision, and much nearer to the eye than are the objects which the observer is called upon to discriminate. Without doubt the best results cannot be obtained without changing also the shape or design of the shade. It will be noticed also in Chart IV that the results were never so good for either kind of shade for the direct and semi-indirect systems as for the indirect. Since the evenness of surface brightness in the field of view was not very different for the three systems in both cases, this again probably indicates that the evenness of surface brightness is not the only one of the distribution factors that has to be taken into account in studying the effect of different conditions of lighting on the eye.

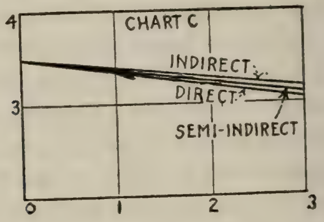
As yet we have not determined the effect of translucent shades on the eye. In attempting to deal in a general way with this class of shades we have the same type of difficulty to face that we have in case of the semi-indirect reflector. That is, we may have shades varying from translucent to opaque and sharing in the merits and demerits of each extreme. Our judgment would be, however, that it would be very difficult to get a translucent shade that would give as good results as the opaque shade with a light lining; for the translucent shade when made sufficiently opaque to give the needed reduction to the image of the source will darken too much the upper half of the field of vision and thereby simulate too much the condition given by the opaque shade with the dark lining to give the best results for comfortable and efficient seeing. Moreover, from the results that have already been obtained with the opaque shade and from the principles it seems fair to infer from these results it seems very probable to us that as good effects for seeing should not be expected from the use of any kind of eye shade as may be gotten from lamp shades. That is, if we are to secure the best results for seeing, the shade should be put on the lamp, not on the eye. However, the relative inexpensiveness of eye shades, their independence of the limitations which militate against the use of certain types of lamp shades, their ready availability to those who have the least chance to escape from the effects of

CHART IV.—EYE SHADE SERIES.

Showing the effect on loss of visual efficiency or power to sustain clear seeing of opaque eye shades with dark and with white lining for the installations direct, semi-indirect, and indirect with the same intensity of light at the point of work. Chart A shows results without shade; Chart B, with shade having dark lining; Chart C, with shade having white lining.







bad lighting, namely the subordinate and the employee, shoul constitute a strong incentive for the development of this type o protection to the eye as a provisional and immediate aid in solvin the problem of bad lighting.

For a fuller statement of results and a specification of the illun ination and brightness measurements and brightness ratios th should be taken into account in considering the results of the test see Transactions of the Illuminating Engineering Society, 191 X, pp. 475-483.

The Angle at Which the Light Falls on the Work.

The object of these experiments was to find out whether tl difference in the angle at which the light falls on the work pr duces an effect on the eye that can be detected by the test we ha used for loss of efficiency. For the purpose of this preliminary i vestigation it was decided to make the general illumination of t

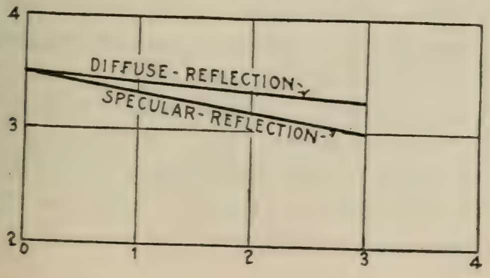
room such as to cause the eye little loss of efficiency as the result of a period of work; and to add to that at the point of work a component of light which was less diffuse in order that the amount of light entering the eye would be more dependent upon the angle at which the reading page was held.

The general illumination was obtained from the indirect system used in the work of the preceding sections with lamps totalling 800 watts. The less diffuse component at the point of work was obtained from a 60-watt lamp with a porcelain reflector of the desk lamp type. This lamp was turned into the horizontal position and was placed behind the observer and to the left so that the light came over the left shoulder. When in the position for which the test was taken, the tip of the lamp was slightly above the level of the observer's eye and at a distance of 1 meter from the left eye.

For the specification of the illumination and brightness measurements and the brightness ratios for our test room illuminated by the indirect system 800 watts, see Trans. I. E. S., 1915, X, pp. 469-471. For a specification of the significant changes in these measurements and ratios produced by the addition of the 60-watt lamp behind the observer, see *ibid.* p. 484. The brightness of the reading page in the position that gave the least amount of specular reflection was 0.0059 cp. per sq. in.; and in the position that gave the greatest amount of specular reflection 0.0077 cp. per sq. in. A mirror surface was used as an aid in locating the position of least and greatest specular reflection. The comparative effects on the eye of these two positions of the reading page are shown in Chart V.

CHART V.—THE ANGLE AT WHICH THE LIGHT FALLS ON THE WORK.

Showing the effect on loss of visual efficiency or power to sustain clear seeing of the angle at which the light falls on the work.



The Effect of Different Conditions of Lighting on the Fixation Muscles of the Eye.

The test we have employed thus far in the conduct of our work is one designed to show the effect of different conditions of lighting on the ability of the eye to hold its efficiency for clear seeing for a period of three minutes. In itself this text is not analytical in principle. The results, as is stated above, are expressed in terms of an aggregate loss of function. The contributive factors may be inferred from the nature of the test but the test is not in itself designed to separate them out. And indeed it is a question whether any practical good can accrue to the practice of lighting from a knowledge of just what part of the visual apparatus it is that falls off in function as a result of an unfavorable condition of lighting. Obviously the chief need is to find out what are the conditions that cause the eye to lose its ability to see clearly and to avoid these conditions in planning and installing a lighting system. From the beginning we have had in mind, however, an analysis of effect Our tests for the sensitivity and functional state of the retina (sensitivity to color and brightness, lag in coming to a full response rate of exhaustion and rate of recovery) showed, for example, tha very little, if any, of the difference in results we have gotten fo the four types of lighting we have employed can be ascribed to loss in the efficiency of the retina, or the light sensitive part o the visual apparatus. Three sets of factors are involved in clea seeing: (1) the sensitivity of the eye to colored and white light (2) the ability to make fine space discriminations which is in pa dependent upon our third factor; and (3) accurate fixation an accommodation. Both fixation and accommodation are the resu of muscular action. When the muscles lose in tone because of e cessive use or by sharing in a general condition or state of tl body, the eye loses correspondingly in its power to sustain clea seeing. If, for example, the muscles of accommodation have fall off in efficiency, the lens is no longer held in the adjustment nee ed to bring the light to a sharp focus on the retina and loss detail and blurring result; or if it be the fixation muscles that ha suffered the loss, the eyes cannot be continuously held in such position that the images of the object viewed fall symmetrically the fovea of each. When this latter condition is present, loss detail results from two causes. (1) The fovea and region imm iately surrounding it are the most highly developed parts of t retina and the best fitted for the light and space discriminatio needed for clear seeing. Moreover, the refracting media of t

eye give the clearest images when the axis of the cone of rays from the object viewed deviates as little as possible, consistent with the mechanism of the eye, from the optic axis. And (2) if the images in the two eyes do not fall more or less symmetrically upon the fovea of each, they are not accurately combined into one, and blurring and loss of detail result from the doubling of the objects seen. It is our purpose as fast as possible to isolate the effect of the three systems of lighting we have used on each of the above named factors. In the work of the present section the effect of these systems on the fixation muscles has been studied only in a tentative and provisional way.

The doubling of the image seen when the fixation muscles lose their power of coordinated action furnishes us with the clue for a test for loss of efficiency of these muscles. That is, just as blurring and loss of ability to discriminate detail is taken as the criterion of the loss of acuity of vision, so will the doubling of the image seen be taken as our index of the loss of the coordinated action of the fixation muscles. If one were to stare continuously for an interval of time with natural vision at a single test object, for example, a vertical line, doubling might be expected especially if there had been protracted strain or considerable loss of power to coordinate. For the purpose of our work, however, greater sensitivity than this would be needed. Obviously sensitivity can be added by putting the eyes under strain to combine their images. When this is done, even when the muscles are fresh, if the object is looked at or fixated for an interval of time it will be seen alternately as one and as two. The proportion or the ratio of the time seen as one to the time seen as two can be regulated by the amount of initial strain under which the eyes are put to combine their images. The regulation of this ratio is empirical and of importance; for as in the case of the test for loss of efficiency for clear seeing, the sensitivity of the test depends to a considerable extent upon the initial value that is given to this ratio. The eyes may be put under strain to combine their images by interposing between them and the object viewed weak prisms and so adjusting them and regulating the distance of the object from the eye that with the maximum of effort to see it as one it is seen alternately as one and as two in

the proportion desired.* In our provisional experiments on this point we found that an adaptation of the Brewster stereoscope afforded a convenient method of putting the eyes under a strain to combine their images. In this case a stereograph consisting of two vertical lines exactly alike may be used as the test object. In the stereograph used in our test the vertical lines were 2.5 cm. long and were printed on the card 4.5 cm. apart or at 2:25 cm. from the center of the card. When this was put in a sliding carrier and was made to approach the eyes, a position was reached at which with the maximum of effort the observer was no longer able to see the two vertical lines as one.* They were seen alternately as one and two. In making the test the hood was removed from the stereoscope so that the eyes were fully exposed to the conditions of the illumination that were being tested. The stereoscope was mounted in front of the eyes of the observer in position at the point of work. The distance of the carrier containing the test object from the observer's eyes was adjusted until the proper ratio of time seen as one and time seen as two was obtained. Having determined

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*It is obvious that the greater part of the strain may be put at wil upon the internal or external muscles by the proper rotation of th prisms. It will be understood that the work reported above is intende to be little more than suggestive of possibilities.

It would seem also that the principle advanced here might be utilize to advantage by the ophthalmologist as a supplement to his tests of th extrinsic muscles of the eye. The abduction and abduction tests, fo example, determine only what the muscles are able to do by momentar effort. Obviously, however, it is not what the muscles are able to d by a momentary effort or jerk that measures their ability to hold th eyes continuously adjusted for work. It is rather their endurance o what they are able to accomplish in an interval of time. An expressio may be had for this either for the eyes conjointly or separately by th method described above. That is, prisms may be put in front of eithe one or both eyes and the ratio be determined of the time the object seen as one or as two for whatever interval of time the operator ma select. Similarly, it seems to the writers that the time element might l introduced to advantage into the visual acuity test used by the ophtha mologist when the cycloplegic is not employed, for example, in cases post-cycloplegic refraction. Is it enough to know that the eye in the cases has 20/20 acuity or can discriminate a certain standard visual ang by a momentary effort? Would it not give a more complete represent tion of the functional condition of the eye to know what it can discrim nate clearly through an interval of time; or better still perhaps, for wh proportion of an interval of time it can discriminate a certain detail standard visual angle clearly? For example, just as a fatigued e may for a moment under the spur of the test overcome the function results of fatigue, so might small errors of refraction be overcome f the moment by muscular effort, especially in the cases in which t muscles of the eye are unusually strong. But just as the fatigued musc cannot do this through an interval of time, so it would seem that residual error of refraction might not be so easily masked through interval of time by means of muscular effort. In short, this form test is suggested as affording possibly a closer approximation to the co ditions and demands imposed upon the eye during a period of work th is afforded by the acuity test based upon the momentary judgment. making this suggestion, however, we recognize that in the work of t clinic the advantage of such a test may be more theoretical than feasil and practicable.

*The observer, whose results are given in this paper, preferred have the working position of the sliding carrier beyond the position which the combination of the two lines was effected the most easi instead of nearer, as is described above. It is obvious that either po tion may be used for testing the ability of the muscles to sustain coor nation of action.

this position a record was made of the time seen as one and the time seen as two for three minutes at the beginning and close of work. The ratio of these intervals may in either case be taken as a measure at that time of the power of the fixation muscles to act in coordination for three minutes of continuous effort; and the decrease in this ratio from the beginning to the close of work may be taken as a measure of the loss in that power sustained as the result of work. In making this test the same recording apparatus was used as was employed in the test for loss of efficiency for clear seeing. That is, the record was traced on a kymograph by means of an electro-magnetic marker and a telegraph key, and a time line was run underneath the record by means of a Jacquet chronograph registering seconds.

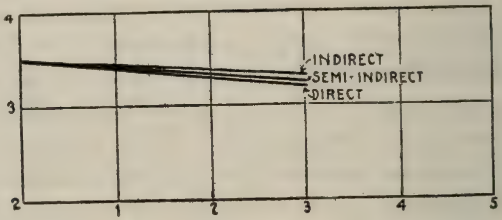
This test was made under the same installations, conditions of work, and with the same observers that were used in the distribution series of the former paper. For a more complete account of this series, see also Transactions I. E. S., 1915, X, pp. 484-490. The test was made at only one of the positions in the room that were used in that series, namely, the position at which the greatest loss of power to sustain clear seeing was obtained. At this point, it will be remembeerd, six of the lighting units were in the field of view. The specifications of the lighting effects produced by these installations are given Transactions I. E. S., 1915, pp. 452-459. Nothing need be added here to these specifications but the brightness of the stereograph, or the test object, in position for the three systems of lighting, and the illumination measurements at the test object. The brightness of the test object, corrected for the absorption of the prisms of the stereoscope, was for the direct system 0.00172 cp. per sq. in.; for the semi-indirect system 0.00163 cp. per sq. in.; and for the indirect system 0.00167 cp. per sq. in. New illumination measurements were needed at the test object because it had to be moved closer to the eyes than was the case in the tests for loss of power to sustain clear seeing. This brought it into a region of different illumination. These measurements are given in Chart VI. The results of this test for loss of coordinating efficiency of the fixation muscles are given also in this chart. These results show (a) that very little loss of coordination was suffered by the fixation muscles as the result of three hours of work under the systems selected; and (b) that there was very little difference in the effect for the three systems. Since there are no obvious reasons for thinking that this test has not somewhere nearly as great sensitivity as the test for loss of efficiency for clear seeing,

and since the same observers, conditions of lighting and working were used as in the former tests, it does not seem to us at this time that the large differences in the loss of efficiency for clear seeing that is sustained under these conditions, as shown by the former tests, can be ascribed to any great extent to an effect on the muscles of fixation. The point, however, cannot be considered as finally settled because we have not made long enough study of the test itself and the limitations of its application to the study in question to make its results certainly comparative with those of the test for the ability of the eye to sustain clear seeing.

CHART VI.—FIXATION MUSCLE SERIES.

Showing the loss of efficiency of the fixation muscles as the result of a three-hour test under the direct, semi-indirect, and indirect systems of lighting employed.

		Foot-candles		
Lighting system	Watts	Horizontal	Vertical	45°
Indirect	800	4.2	0.99	2.5
Semi-indirect	760	4.8	0.98	2.6
Direct	880	3.9	1.0	1.99



The Effect of Motion Pictures on the Efficiency of the Eye.

The belief that motion pictures subject the eye to undue strain is too prevalent to need more than mention in passing. All are familiar with the conditions—the initially dark-adapted and highly sensitized eye, the comparatively brilliant screen with its dark surrounding field, the flickering light, the shifting and very often unsteady pictures. We have already seen that differences in surface brightness of considerable magnitude in the field of vision cause loss of efficiency and produce discomfort and we have discussed the causes for these effects. We have nothing further to add to that discussion here. We are, however, facing for the first time in our work the question of the effect upon the eye of a flickering light and lack of steadiness in the object viewed. The following reason is suggested why a flickering light or unsteady picture may cause loss of efficiency. The eye is so constituted that when its images lose in clearness or distinctness it is incited to

muscular readjustment to bring about the clearness needed. Ordinarily in seeing, the conditions for loss in clearness come about primarily through the difference in distance or direction from the eye of the objects which are successively viewed. In motion pictures, however, the changing clearness in the objects viewed is not due to any change in their distance or direction from the eye; nor to anything in fact which the readjustment of the eye can remedy to any considerable degree. The effort expended, therefore, is of little avail for seeing, if indeed the new setting of the parts is not a detriment to clear seeing and a condition which in turn must be corrected. This should, and doubtless does, lead to muscular strain and loss of efficiency. It was decided therefore, to make an explorative investigation to determine whether there is an effect of motion pictures on the eye which can be detected by our test for loss of efficiency. The tests were taken in a local theatre, selected primarily because of the favorable conditions that prevailed. The definition at the screen was good and the pictures were unusually steady and free from flicker. The conditions were, we think, fairly representative of what is found in the better class of moving picture houses.

The tests were taken immediately before and after two hours of observation of the pictures. During the exhibition the observer sat directly in front of the center of the screen. The observation was made at successive times at three distances from the screen—in the front, the middle and the back of the house. These positions were respectively 25, 48 and 71 ft. (7. 62, 14.6 and 21.6 m.) from the screen. The room in which the pictures were shown was 78 ft. (23.7 m.) long and 48 ft. (14.6 m.) wide. The tests were taken in a room 14 ft. (4.2 m.) long, 9 ft. (2.74 m.) wide, 11 ft. (3.35 m.) high adjoining the stage. The walls and ceiling of this room were of rough plaster, painted a flat white. When taking the tests the observer sat facing one of the side walls of the room, 1.5 m. distant. The room was lighted for the purpose of the test with one 100-watt and one 60-watt clear tungsten lamp suspended behind and slightly to the right of the observer when in position for the test at about 2 ft. (.06 m.) above the level of his eyes. The source of light was entirely out of the field of view and the light fell evenly and without shadow on the test card and the wall in front of the observer. At the point of the test card, the illumination measured with the receiving test plate of the photometer in the horizontal plane was 1.3 foot-candles; in the vertical plane 1.9 foot-candles; and in the horizontal plane 2.3 foot-candles.

The surface brightness of the test card was 0.003256 cp. per sq. in. The distribution of surface brightness on the wall which the observer faced was very even. At the point of maximum brightness to the right of the observer, as nearly as that point could be located, the brilliancy was 0.00308 cp. per sq. in.; and to the left of the observer, 0.002024 cp. per sq. in.

In order that there might be no intermission between the pictures for changing the films, two projection machines were used. The following is the specification of the apparatus employed, as given by the operator:

Type of machine, Powers 6—A Projector.
Lens equipment, 1 pair pearl white condensers, 6½ in. F. L., 1 Bausch and Lomb objective combination, 4¾ in. E. F.
Lamp, 1 10,000-cp. adjustable arc.
Carbons, ⅝ in. cored bio's.
Current, 22 volt. a. c. through Halberg transformer.
Line current, 28-30 amperes.
Arc voltage, 45-50 volts.
Length of throw or distance from objective to screen, 72 ft. (21.9 m.).
Screen, sheet muslin sized and coated with flat white alabastine.
Speed of film through machine, 66 ft. 8 in. (20.3 m.) per min.
Number of pictures per 1 ft. (0.3 m.) of film, 16.
Size of picture on film, ¾ in. (1.9 cm.) high by 15/16 in. (2.38 cm.) wide.
Size of picture on screen, 11 ft. (3.35 m.) high by 14 ft. (4.26 m.) wide.
Approximate brightness of screen with film removed from projector, 3.47 cp. per sq. in.

Exceptional steadiness, it may be said, is given to the movement of the film, and therefore to the picture in this type of projector by the special type of intermittent movement that is employed. Details of this movement need not be given here. As has already been stated, our reason for making the test in this particular theatre was the comparative steadiness of the pictures and the comparative freedom from flicker that was obtained.

The results of the test are shown in Chart VII. Quite a grea deal of loss of efficiency is shown as the result of two hours o observation. The nearer the observer was to the screen, the greate was this loss found to be. The loss, however, so far as we ca tell, is no greater than is caused by steady work under the direc and semi-indirect installation of lighting used in our distributio series. Unfortunately we have not for the purpose of compariso results for the same observer for the same length of time of e posure for the two sets of condition. The loss for Observer R fc the two hours observation of the motion pictures was not nearl so great as for the three hours of reading from good print an paper under the direct and semi-indirect systems of lighting. B comparing results for Observer G for two hours of reading fro the same type and paper with those for Observer R for two hour observation of the pictures, the loss seems to be about the sam

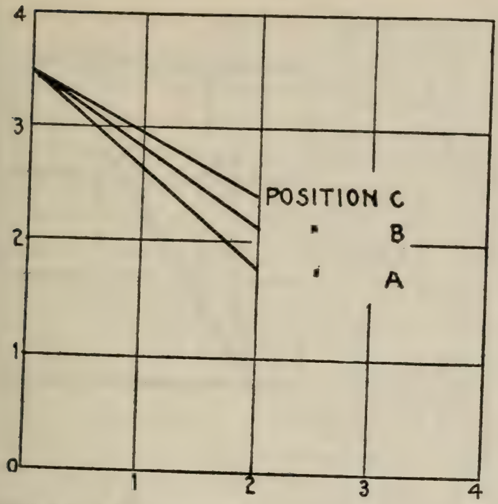


CHART VII.—MOTION PICTURE SERIES.

Showing the loss of visual efficiency or power to sustain clear seeing of the eye caused by two hours observation of motion pictures.

Position A.. 25 ft. from projection screen
Position B.. 48 ft. from projection screen
Position C.. 71 ft. from projection screen

That is, our results indicate that while the eyes are strained a great deal by the observation of moving pictures, even in the better moving picture houses, they are damaged little more by that in all probability than they are by reading steadily the same length of time under the greater part of the lighting that is now in actual use. For the sake of comparing the effect of motion pictures on the eyes with the effect of reading steadily under the direct, semi-indirect and indirect systems of lighting we have employed, Chart VIII has been prepared.

The Tendency of Different Lighting Conditions to Produce Discomfort and a Comparison of the Tendency of These Conditions to Cause Loss of Efficiency and to Produce Discomfort.

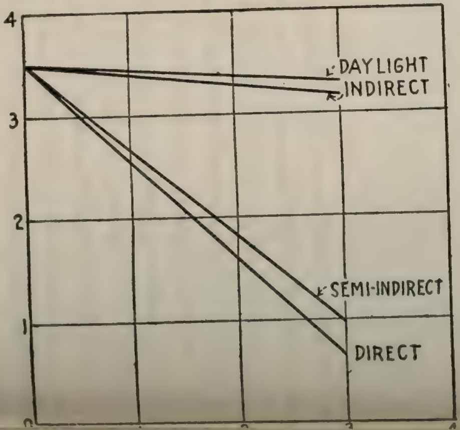
In the former papers we have held that the general level or scale of efficiency of the fresh eye, loss of efficiency as the result of work, and the tendency to produce discomfort are all separate aspects of the problem of lighting in its relation to the eye, and that our knowledge of each must be obtained by different methods of investigation. A correlation between these three moments is doubtless possible, but that correlation should be founded upon the results of careful investigation; it should not be assumed. It is our purpose in this section of the paper to show the relative tendency of

CHART VIII.

Distribution Series (Observer R)

Showing the loss of visual efficiency or power to sustain clear seeing as the result of a two hour test under the systems of direct, semi-indirect, and indirect lighting used, and daylight.

Lighting system	Watts	Foot-candles Hor.	Ver.	45°
Daylight	....	5.5	1.32	4.2
Indirect	800	5.2	1.36	3.5
Semi-indirect	760	5.8	1.45	4.0
Direct	880	4.2	1.41	2.6



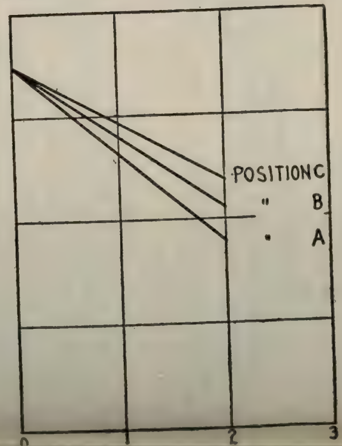
Motion Pictures Series (Observer R)

Showing the loss of visual efficiency or power to sustain clear seeing caused by two hours observation of motion pictures.

Position A, 25 ft. from projection screen.

Position B, 48 ft. from projection screen.

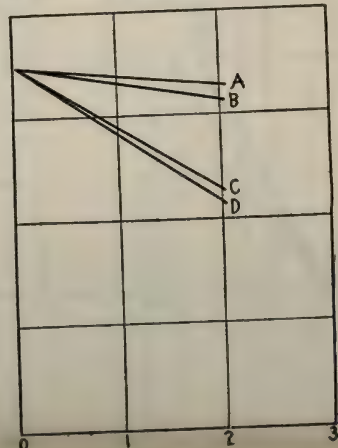
Position C, 71 ft. from projection screen.



Distribution Series (Observer G)

Showing the loss of visual efficiency or power to sustain clear seeing as the result of a test two hour under the systems of direct, semi-indirect, and indirect lighting used, and daylight.

	Lighting system	Watts	Volts	Foot-candles Hor.	Ver.	45°
A	Daylight	—	—	5.5	1.32	4.2
B	Indirect	800	107	5.2	1.36	3.5
C	Semi-indir't	760	107	5.8	1.45	4.0
D	Direct	880	107	4.2	1.41	2.6



the different conditions of lighting we have used to produce discomfort, and to make a rough comparison of the tendency of each condition to cause loss of efficiency and to produce discomfort. Any comparative study of the conditions producing discomfort necessitates a means of estimating discomfort. It is obvious that the core of the experience of discomfort is either a sensation or a complex of sensations. As such it should have a limen or threshold just as other sensations have; and just as we are able in general to estimate sensitivity in terms of the threshold value, so should we in this case be able to use the threshold value in estimating the eye's sensitivity or liability to discomfort under a given lighting condition. Threshold values are usually determined by finding out how much energy or intensity of a given stimulus, applied for a short interval of time, is required to arouse a just noticeable sensation. This form of procedure, however, is not adapted to the needs of our problem. It is much better to reverse the process and find how long the eye has to be exposed to a stimulus of given intensity to arouse just noticeable discomfort. Our threshold thus becomes a time threshold and is measured in units of time instead of units of intensity. In order to determine whether the judgment of the threshold of discomfort can be made with certainty, and to perfect the method and to test in general its feasibility, an abstract investigation was undertaken first, running through an entire year, in which a better and more convenient control of conditions could be secured than is possible in the investigation of a concrete lighting situation. That is, we undertook to determine the comparative sensitivity of the eye to discomfort when a single source of light was exposed in different parts of the field of vision. In order to carry out that investigation a lamp house with a circular opening in one side 3 cm. in diameter was attached to the arm of a perimeter in such a way that the opening was always directed towards the observer's eye. In the lamp house could be placed a lamp of whatever candlepower was desired. The arm of the perimeter could be shifted to any meridian in which it was desired to work and the lamp house could be moved at will along this arm. It was thus possible to expose the light for any length of time in any part of the field of vision that was desired. Working in this way we have not only investigated the effect of many types of variation of the position of the light in the field of view, the effect of intensity of light, etc.; but we have studied and standardized the factors that influence the sensitivity and reproducibility of the judgment and have given our observers the training that

was needed for the concrete investigation. In making the concrete investigation we have used every variation of the conditions of lighting described in this and the preceding paper. That is, the tendency to produce discomfort, measured in terms of the time threshold, has been determined for all the conditions of lighting we have used in the tests for loss of efficiency. Two cases of the investigation may be made—a determination of the tendency to cause discomfort when the eye is at rest, and a determination of this tendency when the eye is at work. Both of these cases were included in our investigation. The following determinations were made. (a) The time threshold of discomfort was gotten when the observer was sitting with the accommoadtion muscles relaxed and with the fixation muscles as nearly relaxed as was practicable under the conditions; that is, the observer sat in the positions used in the distribution series (one with six, one with four, one with two and one with no fixtures in the field of view) and took an easy fixation of an area at the level of the eye on the opposite wall of the room. The fixation distance, for example, for the first of these positions was 22 ft. Since blinking was found to be one of the variable factors which influence the tendency to produce discomfort, the amount of blinking was made constant from test to test. This was accomplished by having the observer blink at equal intervals during the test, timing himself by means of the stroke of a metronome. The interval most natural and suitable for this purpose was determined for each observer separately. In the results given in the following table a three-minute interval was used. And (b) the time threshold of discomfort was determined when the observer was reading from print and paper similar to that used in the loss of efficiency tests. In these tests all the conditions were kept as nearly the same as they were in the work on loss of efficiency as was possible. The results of both of these sets of experiments on the tendency to produce discomfort are shown in Table I-IV. The tendency to produce discomfort should be estimated roughly speaking, probably as inversely proportional to the tim it was required for discomfort to be set up. The time require for discomfort to be set up is given in the tables. In order to mak convenient a comparison of the tendency of the various condition of lighting to cause loss of efficiency and to produce discomfor the percentage loss of efficiency caused by the given lighting cond tion is given in a parallel column in each table. The percentag loss of efficiency was computed by dividing the loss in the rati of time seen clear to time seen blurred sustained as a result

TABLE I.—DISTRIBUTION SERIES.

Showing a comparison of the tendency of the direct, semi-indirect, and indirect installations of lighting used in the distribution series to cause loss of visual efficiency or power to sustain clear seeing, and to produce discomfort. The loss of efficiency is the result of a three hour test. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

Position of observer	Lighting system	Watts	Foot-candles			Per cent. loss of efficiency	Time limen of discomfort in seconds (not reading)	Time limen of discomfort in seconds (reading)
			Horizontal	Vertical	45°			
1.	Indirect	800	5.2	1.36	3.5	8.6	263	100
	Semi-indirect	760	5.8	1.45	4.0	72.0	15	8
	Direct	880	4.2	1.41	2.6	81.0	10	9
II.	Indirect	800	5.1	1.98	4.2	6.3	259	103
	Semi-indirect	760	6.1	2.5	4.7	37.0	26	14
	Direct	880	4.65	2.75	4.4	58.3	20	13
III.	Indirect	800	3.9	2.1	4.0	7.7	255	99
	Semi-indirect	760	5.0	2.6	5.4	22.0	120	35
	Direct	880	4.0	2.9	4.6	31.0	55	24
IV.	Indirect	800	2.9	2.1	3.6	6.6	265	101
	Semi-indirect	760	3.4	3.0	4.4	19.0	240	87
	Direct	880	3.0	3.4	4.5	23.0	235	57

TABLE II.—INTENSITY SERIES.

Showing a comparison of the tendency of the direct, semi-indirect and indirect installations of lighting for the different intensities used in the intensity series to cause loss of visual efficiency or power to sustain clear seeing, and to produce discomfort. The loss of efficiency is the result of a three hour test. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

Lighting system	Watts	Foot-candles			Per cent. loss in efficiency	Time limen of discomfort in seconds (not reading)	Time limen of discomfort in seconds (reading)
		Horizontal	Vertical	45°			
Indirect	800	5.2	1.36	3.5	8.6	263.0	100
	480	3.0	0.765	1.97	8.0	265.0	103
	320 (with socket extenders)	1.7	0.49	1.08	9.1	256.0	98
	200 (with socket extenders)	1.48	0.407	0.95	5.7	251.0	104
	320 (without socket extenders)	1.33	0.39	0.87	23.0	50.0	33
	200 (without socket extenders)	1.16	0.37	0.76	40.0	20.0	14
Semi-indirect	320	2.2	0.58	1.52	11.4	102.0	35
	200	1.6	0.45	1.15	40.9	62.0	16
	480	3.3	0.94	2.4	50.0	50.0	15
	760	5.8	1.45	4.0	72.0	15.0	8
	800	6.8	1.82	4.5	78.0	14.0	3
Direct (16 lamps)	240	1.23	0.54	0.935	57.4	23.5	17
	365	1.6	0.6	1.33	62.0	14.0	11
	400	1.86	0.8	1.46	65.0	12.0	11
	880	4.2	1.41	2.6	81.0	10.0	9
Direct (8 lamps)	200	1.16	0.45	0.85	34.3	56.0	27
	120	0.64	0.32	0.49	45.5	52.0	15
	320	1.97	0.65	1.39	55.5	23.0	13
	480	2.6	1.02	2.00	67.0	20.0	12

work by 3.5, the standard ratio to which all the ratios at the beginning of work were reduced. A rough correspondence of the tendency to produce discomfort and to cause loss of efficiency will be noted in every case. This correspondence by no means amounts to a 1:1 correlation, however. In Table I is given the comparison of the tendency to cause loss of efficiency and to produce discomfort for the distribution series; in Table II for the intensity series; in Table III for the eye shade series; and in Table IV for the series showing the effect of the angle at which the light falls on the work.

TABLE III.—EYE SHADE SERIES.

Showing a comparison of the tendency of the direct, semi-indirect, and indirect installations of lighting used in the distribution series to cause loss of visual efficiency or power to sustain clear seeing, and to produce discomfort when the eye was protected by an opaque eye shade with a dark lining and by an opaque eye shade with a white lining. The loss of efficiency is the result of a three hour test. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

Lining of eye shade	Lighting system	Watts	Foot-candles Horizontal	Foot-candles Vertical	Foot-candles 45°	Per cent. loss of efficiency	Time limen of discomfort in seconds (not reading)	Time limen of discomfort in seconds (reading)
White	Indirect	800	5.2	1.36	3.5	9.1	85	50
	Semi-indirect	760	5.8	1.45	4.0	10.6	81	48
	Direct	880	4.2	1.41	2.6	12.0	75	45
Dark	Indirect	800	5.2	1.36	3.5	33.0	23	19
	Semi-indirect	760	5.8	1.45	4.0	33.4	19	15
	Direct	880	4.2	1.41	2.6	35.0	16	13

TABLE IV.—THE ANGLE AT WHICH THE LIGHT FALLS ON THE WORK.

Showing a comparison of the tendency to cause loss of visual efficiency or power to sustain clear seeing, and to produce discomfort of the angle at which the light falls on the work. The loss of efficiency is the result of a three hour test. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

Reflection from reading page	Foot-candles Horizontal	Foot-candles Vertical	Foot-candles 45°	Per cent. loss of efficiency	Time limen of discomfort in seconds (reading)
Diffuse	5.3	1.84	3.9	6.6	95
Specular	5.3	1.84	3.9	14.3	30

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A RÉSUMÉ OF EXPERIMENTS ON THE EFFECT OF DIFFERENT CONDITIONS OF LIGHTING ON THE EYE.

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The work of which this paper is a brief outline was done under the auspices of the American Medical Association's subcommittee on the Hygiene of the Eye, of which Dr. William Campbell Posey of Philadelphia is chairman, and has been in progress five years. The object of the work has been to compare the effect of different lighting conditions on the eye and to find the factors in a lighting situation which cause the eye to lose in efficiency and to experience discomfort.

Confronting the problem of the effect of different lighting conditions on the eye, it is obvious that the first step towards systematic work is to obtain some means of estimating effect. The prominent effects of bad lighting systems are loss of efficiency, temporary and progressive, and eye discomfort. Three classes of effect, however, may be investigated: (1) The effect on the general level or scale of efficiency for the fresh eye; (2) loss of efficiency as the result of a period of work; and (3) the tendency to produce discomfort. A description of tests designed especially for the investigation of these effects has already appeared in print.[1] Some of these tests have been designed to determine the eye's aggregate loss in functional power, others to aid in the analysis of this effect. Space can be taken here for the mention only of the one with which the greater part of the work was done—namely, a test for determining the power of the eye to sustain clear seeing. Just two principles are involved in this test. One is that visual acuity or clearness of seeing may be measured by the smallest visual angle the eye is able to discriminate;

the other, a principle equally old, is that a loss of efficiency in a machine, apparatus, or a living organ or organism will show out more plainly when a prolonged rather than a momentary performance is required. These principles have been combined in their simplest terms into a test of the comparative ability of the eye to maintain its power of clear seeing or aggregate functional activity under different conditions of lighting and under different kinds and conditions of use. In operation the test method may be described briefly as follows: The power of the eye to sustain a certain standard of acuity for three minutes is measured before and after a period of reading from uniform type and paper under the lighting conditions to be tested. That is, by means of a visual acuity test object with the proper auxiliary apparatus and a kymograph and a chronograph, records are made of the time the eye can be held up to this standard of performance and the time it drops below. The ratio of these quantities to each other or to the total time for which the record was made is taken as the measure of the ability of the eye to sustain its power of clear seeing before and after work under the lighting conditions to be tested.

The following aspects of lighting sustain an important relation to the eye: The evenness of illumination, the diffuseness of light, the angle at which the light falls on the object viewed, the evenness of surface brightness, intensity, and quality, or color value of the light. The first four of these factors, which may be grouped together as distribution factors, will be discussed briefly with reference to types of lighting now in common use.

The ideal condition with regard to the distribution factors, so far as the functional welfare of the eye is concerned, is to have the field of vision uniformly illuminated with light well diffused and no extremes of surface brightness. When this condition is attained the illumination of the retina will shade off more or less gradually from center to periphery, which gradation is necessary for accurate and comfortable fixation and accommodation. In the proper illumination of a room by daylight we have been able thus far to get the best control of the distribution factors. Before it reaches our windows or skylights, daylight has been rendered widely diffuse by innumerable reflections; and the windows and skylights them-

selves, acting as sources, have a broad area and low intrinsic brilliancy, all of which features contribute towards giving the ideal conditions of distribution stated above. Of the systems of artificial lighting, the best control of the distribution factors, speaking in general terms, is given by the indirect systems, and the semiindirect systems with a small direct component of light. In the indirect systems the source is concealed from the eye and the light is thrown against the ceiling or some other diffusely reflecting surface in such a way that it suffers one or more reflections before it reaches the eye. When properly installed the use of these reflectors introduces no extremes of surface brightness in the field of view greater than that which the eye is prepared to stand without a significant depression of functional power. Moreover, the brightest spots are on the ceiling and are, therefore, in rooms of ordinary height, pretty well removed from the zone of most harmful influence on the eye. The direct lighting systems are designed to send the light directly to the plane of work. There is in general in the use of these systems a tendency to concentrate the light on the working plane or object viewed rather than to scatter it in all directions, and therefore a tendency, especially with some types and kinds of installation, to create brightness differences in the field of view rather than to level them down. Much can be done to ameliorate this tendency, however, in constructing the reflector and grading its density and in choosing the height of installation above the working plane. Too often, too, the eye is not shielded properly from the light source, and frequently no effort at all is made to do this, although such practice is now strongly condemned by the lighting engineer. How to retain as much as possible of the superior physical efficiency of direct lighting and at the same time to protect the eye from the harmful effects of badly controlled distribution factors, more especially from the glare of poorly concealed sources, the excessive brilliancy presented by the surfaces of reflectors of low density and by the openings of reflectors of high density, etc., is one of the most interesting and difficult problems presented to the workers in this field at the present time. The semiindirect reflectors are intended to represent a compromise between the direct and indirect reflectors. A part of the light is transmitted to the plane of work through the translucent

reflector placed directly beneath the source of light, and a part is reflected to the ceiling. Thus, depending on the density of the reflector, this type of lighting may vary between the totally direct and the totally indirect, and share in the respective merits and demerits of each in proportion to its place in the scale. By giving a better control of what we have called the distribution factors, this type of lighting is supposed also to be a concession to the welfare and comfort of the eye, and so it is in reflectors of high density. Our tests, however, show that the concession is not nearly so great as it was supposed to be in case of reflectors of low and medium density. In fact, installed at the intensity of illumination ordinarily used or at an intensity great enough for all kinds of work, little advantage seems to be gained for the eye for reflectors of low and medium density; for with these intensities of light and densities of reflector the brightness of the source has not been sufficiently reduced to give much relief to the suffering eye. Until this is done in home, office and public lighting, we cannot hope to get rid of eye strain with its complex train of physical and mental disturbances. Moreover, the principles in accord with which the installation is made require that the reflector be brought further into the field of vision than is the case, for example, when a direct reflector is used. On this account a worse result is apt to be obtained with semiindirect reflectors of low and medium density than even with equally well designed direct reflectors of the same density.

In the experimental work the following points have been covered: The effect of varying the distribution factors on the ability of the eye to maintain its maximal efficiency for a period of work; the effect of varying the intensity of light with various groupings of distribution factors; and certain miscellaneous experiments relating to the hygienic employment of the eye. These latter experiments include the effect of varying the area, and conversely the intrinsic brightness of the ceiling spots above the reflectors in an indirect system of lighting; the effect of varying the angle at which the light falls on the work in a given lighting situation; the effect of using an opaque eye shade with light and dark linings with each of the lighting installations used in the distribution and intensity series; the effect on the efficiency of the fixation muscles of a period of work

under each of these installations; the effect of motion pictures on the eye at different distances from the projection screen; and a determination of the tendency of each of the conditions of lighting employed to produce discomfort and a comparison of the tendency to produce discomfort and to cause loss of efficiency.

The investigations were not abstract in character. All the variations obtained were gotten in actual concrete lighting situations by employing lighting installations in common use. In order that a correlation might be made between lighting conditions and the effect on the eye, the following specification of illumination effects was made in each case:

(1) A determination was made of the average illumination of the room under each of the installations of lighting used. The room was laid out into three-foot squares and illumination measurements were made at sixty-six of the intersections of these squares and at the point of work. Readings were taken in a plane one hundred and twenty-two centimeters above the floor with the receiving test plate of the illuminometer in the horizontal, the forty-five degree and the ninety degree positions, measuring respectively the vertical, the horizontal, and the forty-five degree components of illumination. The one hundred and twenty-two centimeter plane was chosen because that was the height of the test object. In the work on the distribution series the illumination was made as nearly as possible equal to the point of work.

(2) A determination was made in candle power per square inch of the brightness of prominent objects in the room, such as the test surface, the reflectors for the semiindirect installation, the reflectors and filament for the direct installation, the reading page, the specular reflection from surfaces, etc. The brightness measurements were made by means of a Sharp-Millar illuminometer with the test plate removed. The instrument was calibrated against a magnesium oxid surface obtained by depositing the oxid from the burning metal. By this method the reflecting surfaces were used as detached test plates. The readings were converted into candle power per square inch by the following formula: Brightness $= \frac{\text{Foot-candles.}}{\Pi \times 144.}$

(3) Photographs were made of the room from three positions under each system of illumination.

In the selection and use of observers for the work the following are some of the precautions that were taken: Care was exercised, in the first place, to choose only those who had shown already a satisfactory degree of precision in other work in physiologic optics and whose clinic record showed no uncorrected defects of consequence. All were under thirty years of age. Before being allowed to take part in the actual work of testing, each observer was trained to a satisfactory degree of precision in the three minute record under a given lighting condition, and in the three hour test under several of the conditions to be tested. In the actual work of testing the results were compiled from several observations, and the precision was checked up by the size of the mean variation. No results were accepted as significant unless the variation produced by changing the condition to be tested was largely in excess of the mean variation or mean error for each condition tested. This, the accepted conventional check on the influence of variable extraneous factors, was carefully applied at each step in the work. The following results were obtained:

(1) Of the lighting factors that influence the welfare of the eye, those we have grouped under the heading of distribution are apparently fundamental. They seem to be the most important we have yet to deal with in our search for the conditions that give us the minimum loss of efficiency and the maximum comfort in seeing. If, for example, the light is well distributed in the field of vision and diffuse, and there are no extremes of surface brightness, our tests indicate that the eye, so far as the problem of lighting is concerned, is practically independent of intensity. That is, when the proper distribution effects are obtained, intensities high enough to give the maximum discrimination of detail may be employed without causing appreciable damage or discomfort to the eye.

(2) For the control of distribution effects given by the semi-indirect reflectors of low and medium density and the direct reflectors presenting, as most of them do, excessive brilliancies due to opening, surface of reflector, or a wholly or partially exposed source, our results show unquestionably that too much light is being used in ordinary work for the comfort and welfare of the eye. That is, with these reflectors means have not

yet been found of producing this amount of light without introducing harmful brilliancies into the field of vision.

(3) The angle at which the light falls on the object viewed is an important factor, but not nearly so important, for example, as evenness of surface brightness in the field of vision. Extremes of surface brightness in the field of vision seem, in fact, to be the most important cause of the eye's discomfort and loss of efficiency in lighting systems as we have them at the present time. In lighting from exposed sources it is not infrequent to find the brightest surface from one million to two and one-half million times as brilliant as the darkest; and from three hundred thousand to six hundred thousand times as brilliant as the reading page. These extremes of brightness in the field of vision are, our tests show, very fatiguing to the eye.

(4) Of the systems of artificial lighting tested thus far, the best results have been obtained for the indirect systems, and the semiindirect systems with reflectors having a high density. By means of these reflectors the light is well distributed in the field of vision, and extremes of surface brilliancy are kept within the limits which the eyes are prepared to stand. A great deal of loss of efficiency has been found to result from the use of semiindirect reflectors of low and medium density, and from the use of direct reflectors, especially those of shallow and medium depth. With regard to the degree of density that is most favorable for the eye, the direct reflectors seem, however, to present a special case. With reflectors of medium depth our best results have been gotten so far with reflectors of medium density. This, however, is not in contradiction to our principle that extremes of brightness are fatiguing to the eye. For in case of the denser reflectors the ceiling and the reflectors are dark, while standing out in sharp contrast to them is the bright opening of the reflector. Moreover, if the physical efficiency of the reflector is not to be lowered by increasing its density, its opening must become lighter in some proportion to the increase of density, for in a totally opaque reflector all, and in the denser reflectors nearly all, of the light sent to the working plane must come from this opening. In the reflectors of medium density, however, the opening need not have such a high brilliancy, and there is little contrast

between it and its surroundings. When installed on or near the ceiling in rooms of moderate height, the best results seem to be obtained when the opening, the surface of the reflector, and the ceiling have as nearly as possible an equal brilliancy. It seems probable that the effect on the eye of the denser reflectors can be very much improved by increasing the depth of the reflector and by other devices that will lower the brilliancy of the opening.

(5) The problem of installing is not the same for the semi-indirect as for the totally indirect reflector. In the latter case the height should be so adjusted as to give as nearly as possible an even distribution of surface brightness on the ceiling and evenness of illumination on the working plane. In the case of semiindirect reflectors, especially those of medium densities, and in rooms of the height ordinarily found in dwelling houses, if the distance from the ceiling is made great enough to produce these effects, the bright reflectors are dropped too low in the field of vision for the highest comfort and efficiency of the eye. Apparently the denser they are the more nearly they can afford to be installed as indirect reflectors, and the less dense they are the more nearly they should be installed as direct reflectors, so far as eye effects of the kind revealed by our tests are concerned. In this connection it may be pointed out that in current practice direct reflectors for general illumination are usually installed on the ceiling or as near to it as is possible, especially in rooms of low or medium height.

(6) In the work of providing general illumination the most difficult feature presented in the problem of protecting the eye is encountered in the lighting of rooms of low and medium height. The difficulty decreases with increase of the height of the ceiling. In rooms whose ceilings are very high in proportion to the other dimensions of the room, it seems safe to say that comparatively good results should be gotten with almost any reflector of modern design; for it is much easier in such rooms to get the bright sources of light, primary and secondary, out of the zone of most harmful influence on the eye.

(7) The loss of efficiency sustained by the eye in an unfavorable lighting situation seems to be muscular, not retinal. The retina has been found to lose little, if any, more in effi-

ciency under one than under another of the lighting systems employed (tested by power to discriminate color and brightness, lag of sensation, rate of exhaustion and rate of recovery).

(8) Eye shades are apparently not an adequate substitute for lamp shades for the protection of the eye from the source of light. The best results were gotten by means of an opaque eye shade with a light lining. The usual opaque eye shades with a dark lining, while they shield the eye from the source of light, do not by any means eliminate harmful brightness differences in the field of vision. They in fact create for the eye a very unnatural brightness relation—i. e., they make the whole upper half of the field of vision dark, in sharp contrast with the brightly lighted lower half. The direct effect of this is a strong brightness induction (physiologic) over the lower half of the field of vision which causes glare in surfaces which have no glare and increases the glare in surfaces in which glare is already present. Moreover, the unusual and strongly irregular character of the image formed on the retina probably also sets up warfare in the incentives given to the muscles which adjust the eye—that is, the upper half of the field of vision is dark and presents no detail. The effect of this is probably to exert a tendency to cause the muscular relaxation characteristic of the darkened field of vision. The lower half of the field of vision is light and filled with detail. The incentive here is for the best possible adjustment of the eye for the discrimination of detail in the object viewed, while the rim of the shade, the sharply marked boundary between the light and dark halves of the field of vision and much nearer to the eye than the objects viewed, serves as a constant and consciously annoying distraction to fixation and accommodation. These complex and somewhat contradictory impulses given to the muscles of the eye might very well, and doubtless do, cause an excessive and unnatural loss of energy and efficiency in case of the prolonged adjustment needed for a period of work. Translucent shades, when made sufficiently opaque to give the necessary reduction to the image of the source, darken too much the upper half of the field of vision and simulate thereby too much the effect given by the opaque shade with the dark lining to give the best results for efficient and comfortable seeing.

(9) The observation of motion pictures for two or more hours causes the eye to lose heavily in efficiency. The loss decreases rather regularly with the increase of distance from the projection screen. It seems little if any greater, however, than the loss caused by an equal period of working under much of the artificial lighting now in actual use. In making these tests care was taken to choose a projection apparatus which gave a picture comparatively steady and free from flicker.

(10) In all the conditions tested a rather close correlation is found to obtain between the tendency of a given lighting condition to cause loss of visual efficiency and to produce ocular discomfort. The tendency to produce ocular discomfort was estimated by the time required for just noticeable discomfort to bet set up with the eye both working and at rest under the conditions to be tested. The results of this work were also carefully checked up by the determination of the mean variation.

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See also J. R. Cravath: Some Experiments With the Ferree Test for Eye Fatigue. Trans. Illum. Eng. Soc., 1914, 9, pp. 1033-1047; and C. E. Ferree: Discussion of Mr. Cravath's paper "Some Experiments," etc., ibid., pp. 1050-1059.

A SIMPLE DAYLIGHT PHOTOMETER

By C. E. Ferree and Gertrude Rand, Bryn Mawr College

A need for a simple daylight photometer has long been felt, especially in the work of the undergraduate laboratory. The impossibility of making determinations of color sensitivity even with a degree of precision that is acceptable in undergraduate work without constancy of illumination especially when pigment papers are used as stimuli is too well known to need more than mention here. To make such an instrument broadly serviceable the following are some of the requirements which should be met. (a) The instrument should be compact and easily portable. (b) It should be so simple and inexpensive in construction as to be readily within the mechanical resources of the average laboratory. And (c) the standard and comparison fields should present little if any color difference.

An instrument which we have constructed especially to meet the above needs is shown in Fig. I. It has been in use in our laboratory for more than a year and has proven so serviceable and convenient that we have thought it worth describing for the possible benefit of others. It was designed and has been used by us primarily for the reproduction of a given intensity of illumination rather than for its measurement in photometric units, although it can be calibrated and be used for photometric measurements. The instrument consists of a photometer head, a short bar, a standard tungsten lamp with carriage which is moved back and forth along the bar by means of a rack and pinion, a millimeter scale which may be read outside of the photometer box, a finely graduated ammeter to regulate the supply of current to the lamp, and a tripod support. When operated as a daylight photometer one opening of the photometer head, the bar, and the standard lamp with its sliding carriage must be boxed in; and the other opening of the photometer head be suitably exposed to the illumination that is to be balanced against the light of the standard lamp. This boxing can be made as elaborate as one chooses or it can be made very simple. In this connection the different needs that may arise for a portable photometer

should be kept in mind. One may want, for example, to determine the average illumination, or the distribution of light in a room which may or may not be evenly illuminated. To do this the room should be laid out in small squares and measurements be taken in several directions of horizontal, vertical and 45 degree components of illumination at the corners of these squares. For such work it is obvious that a somewhat elaborate photometer is required, comprising, for example, a test plate that can be turned in different directions and a type of boxing that will permit of a quick adjustment of the lamp and reading of the scale from the outside. Such a photometer we are required to employ for the specification of the lighting effects in our work on the effect of different conditions of artificial lighting on the eye. An instrument of this kind, however, may cost from one hundred and fifty to three hundred dollars, which is of course more than is justified for the work of the general laboratory. If, however, an instrument is wanted primarily to reproduce the horizontal component of illumination or the light falling on a vertical surface such as a campimeter screen, rotating disk, etc., at a given point in a room, a very simple boxing is all that is required; for all that is needed here is to set the standard light at such a position on the bar as will balance the light in the room at that point and keep it there as long as that intensity of light is wanted. We have found it quite sufficient in one instrument we are using to make this boxing of light-proof cloth sliding on a suitably constructed frame. This cloth may be folded back to the far end of the frame for the adjustment of the position of the lamp or it may be brough forward and hooked to the frame of the photometer heac while the photometric balance is being made. In case of the instrument described in this paper a somewhat more elaborat but still simple boxing is used. This boxing is made of heav sheet tin painted black outside and inside and carefully light proofed. It is 18 inches long, 4.5 inches wide, and 10 inche deep.[1] The photometer head forms one end of this box; th other end is of fiber fitted with binding posts which connec with the line and with cords running to the standard lamp and with a knife switch to make and break the circuit. Th

[1] It may seem that the boxing of this instrument is unnecessaril deep. It was made deep in order that lamps of ordinary sizes migh be used as standards. The boxing shown in Fig. II is designed t take 25, 40, and 60-watt Mazda lamps and to allow for the adjustmen of height needed to bring the centers of their filaments in line wit the center of the opening of the photometer head. If smaller speci lamps were used so much depth would not be needed and the instru ment could be given a neater appearance.

top of the box is covered with tightly fitting hinged lid which permits of a convenient and easy entrance to the box. Projecting through the side of the box is a milled head which operates the rack and pinion adjustment of the position of the standard lamp on the bar. The instrument with the boxing is shown in Fig. II.

The photometer bar is 24 inches long. At one end of this bar is a right-angled holder for the photometer head. The

FIGURE I

photometer head is supported on a brass rod 5 inches long which passes vertically through an opening in the right-angled holder. When adjusted to the height that is wanted it is held in position by means of a set screw. The carriage for the standard lamp is shown in Fig. I. This carriage is fitted also with a right-angled holder and set screw to hold the standard lamp and to provide for adjusting its height so that the center of the lamp may always be in line with the center of the adjacent opening in the photometer head. On the bottom of this carriage is fastened a rack 12 inches in length which is engaged by the pinion operated by the milled head already mentioned. To this carriage is also fastened a brass scale graduated in millimeters which extends through

an opening in the fiber plate forming the end of the photometer box opposite to the head. Thus as the lamp is run back and forth along the bar its position can be read, outside the box, from the divisions on the scale. To facilitate the reading of these divisions the scale runs immediately back of a short pointer fastened to the end of the photometer box.

The photometer head employed is of the Bunsen type. This type of head is especially suitable for our purpose be-

Figure II

cause it combines to a favorable degree the features of accu
racy and simplicity of construction. The photometer scree
may be very simply made. In the present case it consist
merely of two pieces of Hering mat white paper 12.5 cm. lon
and 8 cm. wide smoothly pasted together with the mat side ou
The screen so formed can be overlaid if desired with magne
sium oxide deposited from the burning metal. In the media
line (horizontal) of this screen, 1.5 cm. from one end a circula
opening, 1.5 cm. in diameter, with serrated margins, is cu
This opening may be filled with a layer of an extra goo
grade of tissue paper or other translucent material, the edg
of which are held between the two layers of Hering pape
It is desirable to have a material to fill this opening whos

coefficient of transmission is as nearly as possible equal to its coefficient of reflection. This screen fits into a groove which runs from front to back in the median plane of the photometer head. Set into the back of the photometer head on either side of the screen and making an angle of about 65 degrees with it are two mirrors of suitable size in which the images of the two sides of the screen are viewed by the eye in making the photometric comparison. On either side of the photometer head are two openings, 3.25 x 2.5 inches, for the illumination of the photometer screen. One of these admits the light from the standard lamp, the other the light from the room. Both of these openings are filled with a plate of single-thick milk glass (Belgian make) ground on one side. This glass diffuses the light and gives a more uniform illumination of the two sides of the photometer screen. In order that the two sides may be illuminated by light of the same color quality, color filters must be employed. That is, either the standard lamp must be robbed of its excess of yellow and red light or the daylight must be colored to match the light from the standard lamp. Either of these effects can be readily accomplished by means of thin sheets of colored gelatines, placed in the grooves in front of the sheets of milk glass. With gelatines of a low coefficient of selective absorption it is not at all difficult to make a good match of the two lights as to color quality and thus to eliminate the difficulty that attends the attempt to make a judgment of equality of brightness between two surfaces which differ as to color quality. In making this match by means of filters it must be remembered that if the match is made by filtering the daylight, a slight physical error will be introduced because of the variable composition of daylight on different days and at different times of the same day. That is, a filter that transmits heavily in the yellow will let a greater total of light through when the daylight contains an excess of yellow than when it does not. This objection, however, is considered by some photometrists to be of more theoretical than practical consequence. To offset this objection the greater photometric sensitivity to yellow may perhaps be mentioned with some justification. The variable composition of daylight also causes some difficulty in maintaining an exact color match between the standard light and daylight. A filter that produces an exact match at one time may not at another time. For this reason it is of advantage to make the filters of thin layers of gelatine which can be added to or subtracted from with the proper corrections for absorption as the need arises.

The bar carrying the standard lamp and the photometer

head is supported by a tripod base and stem. The stem consists of a hollow tube split at the upper end and fitted with a collar and set screw. The stem telescopes over a rod 8 inches long which is screwed into the photometer bar 8.5 inches from the end supporting the photometer head. By means of the collar and set screw the apparatus may be adjusted and clamped at different heights.

In order that the standard lamp may be operated directly from the line a rheostat and finely graduated ammeter are used to regulate and keep constant the supply of current. For the sake of portability the ammeter is fastened to a wood base which is screwed to two of the feet of the tripod. The ammeter is of Weston make, triple range, 0.5, 1, and 1.5 amperes, combined in one case. The scale of the first of these ranges is graduated to 0.01 amperes. On account of its size, its graduations, and its comparative inexpensiveness, this ammeter is very well suited for the purpose. A specification of the rheostat need not be given here. Any good rheostat of suitable carrying capacity and range of adjustment which permits of fine changes of resistance may be used.

The use of the apparatus for the reproduction of any given illumination is as follows: The rheostat is adjusted to give the amperage at which the standard lamp is to be operated. A balance is then made at the point in the room in question between the light falling on the photometer head and the standard light, and a reading is taken of the photometer scale. When it is wished to reproduce this illumination the resistance is again adjusted to give the reading of the ammeter chosen as standard and the light of the room is varied until a photometric match is obtained. If it is wished to calibrate the instrument so that the reading of the scale can be translated into foot-candles, for example, a standard lamp is set up at such distance from the milk glass test plate on the photometer head as will give a balance with the photometer lamp adjusted for the different points on the scale. The amount of light falling on the test plate can be computed directly from the known flux of the standard lamp and the distance of the lamp from the test plate. This is correlated with the division on the scale for which the photometric balance is made. The different points on the scale are thus gone over one by one and the correlative foot-candle values are obtained. During the calibration the photometer lamp must of course be operated at a constant amperage, and in the use of the calibrated instrument this amperage must be reproduced else the calibrated values will not be valid.

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A SUBSTITUTE FOR AN ARTIFICIAL PUPIL

BY C. E. FERREE AND GERTRUDE RAND

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It is a well-known principle of physiological optics that the amount of light condensed into the retinal image of a given test object or source of light varies with the size of the pupil. It is obvious, therefore, that a complete plan or provision for the standardization of the factors which influence the precision of a color determination must take into account the possible sources of error due to a variable pupillary aperture.[1] The remedy usually employed when any account is taken of the factor is an artificial pupil. 'hether, however, the use of an artificial pupil is to be recommended is seriously open to question. In our own work we have found its use to be attended by so many difficulties and to be open to so many objections as to be quite inadvisable, unless perhaps in case it is wanted to compare the response to stimuli differing rather widely in intensity. Space can not be taken here for a detailed discussion of these difficulties and objections. It will be sufficient perhaps to say that with the best possible adaptation of the size of the artificial to the natural pupil, its distance from the eye, etc., four difficulties remain which seem inherent and very difficult if not impossible to overcome. (1) The influence of the brightness of the surrounding field on the sensitivity of the retina to the test field can not be satisfactorily controlled.

[1] We will say, however, that we believe this variable error to be very small when a constant light flux is used for stimulus, and a light-adapted eye is employed, working at a moderately high and constant intensity of illumination. We believe this because of the very small mean variations we have obtained in determinations of color sensitivity when all the other factors influencing the response of the eye, which we have discussed in previous papers, are controlled and the pupil is left to regulate itself. In fact we have not been able so far to reduce appreciably the size of this mean error by any artificial regulation of the constancy of the light flux entering the eye from a given constant source. Regulation is desirable, however, when the effect on the eye of different intensities of light is to be compared.

Theoretically considered it would not be possible to attain this control unless the artificial diaphragm could be brought approximately into the plane of the iris. (2) The response of the retina can not be investigated out to the peripheral limits of the field of vision. With the intensity of light attainable with the apparatus described in a preceding paper,[1] red, blue, and yellow can be sensed out to 92° and green to 70° in the nasal meridian. (3) The relation of size of pupil to the cross section of the beam of light which the artificial pupil admits to the eye can not be under observation while the color determination is being made to see whether the regulation needed is actually accomplished in any given case. The adaptation of the size of the artificial to the natural pupil must rest upon a probability established by a number of measurements made on the reaction of the pupil under a set of conditions as nearly as possible identical with those used in the case in question. And (4) the device used to give the pupillary aperture can not be gotten so close to the natural pupil as not to disturb the adjustment of the eye and otherwise to serve as an annoying distraction in the field of vision.

In the apparatus described in the preceding paper the method of presenting the stimulus to the eye is such as to permit of a substitute for the artificial pupil which so far as we are able to determine is entirely free from the objections and difficulties attending the use of a diaphragm in front of the iris. In this substitute plan instead of cutting down the cross section of the beam of light at the eye by means of an apparatus which interferes with the natural functioning of that organ, the regulation needed is accomplished further back in the optical system, out of range of the anterior reactions of the eye and out of the road of the manipulation needed to control the factors which directly influence the response of the eye to its stimulus. That is, the stimulus light is focused by means of the lens (L_2)[2] upon the pupil of

[1] Ferree and Rand, 'A Spectroscopic Apparatus for the Investigation of the Color Sensitivity of the Retina, Central and Peripheral,' *J. of Exp. Psychol.*, 1916, 1, 247–284.

[2] *Op. cit.*, pp. 254–255.

the eye, forming an image of the analyzing slit of the spectroscope. Obviously the size of this image can be regulated by controlling the height of the slit, for example, or by means of the lens system so as always to fall within the aperture of the pupil reacting to the intensity of the light used in any given case. It adds very much to the precision of the regulation also that its correctness can be checked up if desired for every color determination while the determination itself is being made.[1] That is, not only can the size of image needed for a given intensity of light and set of conditions be determined empirically in a number of trials but its relation to the size of the pupil may be under observation all of the time in a series of determinations of sensitivity. With the lens system and breadth of slit we are now using, we have found that it is not necessary to alter the breadth of the image. This would be done, if it were necessary, by means of an alteration in the lens system. The height is reduced the desired amount by cutting down the height of the analyzing slit which was made variable over a wide range primarily for this purpose, as was stated on pp. 253 and 261 of the preceding article: 'A Spectroscopic Apparatus for the Investigation of the Color Sensitivity of the Retina, Central and Peripheral.' This control of the constancy of the amount of light entering the eye we have found to be entirely feasible and practicable. With it in fact the observation is attended with no more difficulty than if the apparatus were used with no attempt to exercise this control.

[1] Owing to the brightness and sharpness of the image on the cornea with its dark background of iris and pupil, this comparison of the size of the image with the size of the pupil is, it is obvious, not difficult to make. The possibility of having this feature constantly under observation gives this method of regulating the amount of light entering the eye no small advantage over the artificial pupil.

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DISCUSSION

A NEW METHOD OF HETEROCHROMATIC PHOTOMETRY—A REPLY TO DR. JOHNSON

In the September number of this journal appears a discussion entitled 'A Note on Ferree and Rand's Method of Photometry,' by Dr. H. M. Johnson, of the Nela Park Laboratory. This discussion, we may perhaps be pardoned for noting, is remarkable chiefly for its numerous mistakes and incorrect or misleading representations, a few of which we take opportunity here to rectify. The net service of the discussion is to call the authors' attention to the omission of a decimal point in the original article, for which they duly acknowledge their debt.

1. In his opening paragraph Dr. Johnson says: "The authors claim for their method that with respect both to sensitivity and reproducibility it surpasses the equality of brightness method, even when the photometer head used is of the best Lummer-Brodhun type." In regard to this statement we beg to point out that Dr. Johnson has omitted from what was actually said all that makes a difference between a reasonable and an absurd claim. We had claimed in our paper greater reproducibility of setting for the method in question as compared with the equality of brightness method *only in case of heterochromatic photometry*, in which respect as is well known the equality of brightness method is notably deficient. The possibility of a service to heterochromatic photometry alone is the reason given in the paper for applying to the rating of artificial lights a principle formerly used by us for an entirely different purpose. Also the special reference to heterochromatic photometry was featured in the title.

2. Dr. Johnson next says: "The authors assumed that the two elements making up the photometer screen 'received equal amounts of light from the source to be measured.' Even if the elements were equidistant from the lamp . . . the truth of this assumption does not follow from the data given. In some of the work the results of which are presented in the authors' table, the angular separation of the compared elements was 14° to 15° at the source. Now the radiation from a carbon or tungsten lamp is not equal in

all directions as is that from an ideal point source. In fact, for lamps of such types, differences of several per cent. in different directions normal to the long axis of the lamp are the rule, and a considerable difference might occur in a range of 15°."

With reference to the above statements we wish to note in the first place that it was never assumed by us that there were only two elements in the photometer screen. This erroneous interpretation of the principle on which the method is based can be attributed to Dr. Johnson only. Secondly, that when the angular separation of the elements referred to (the stimulus patch and the measuring disc), is correctly computed from the data contained in the original article it is found to vary between 4.5° and 11°,[1] and not to have a range of 15°. And thirdly, that when the question of the influence of the distribution curve on the general applicability of the method to working practice was raised by us in a paper presented to the Philadelphia Section of the Illuminating Engineering Society in February, 1914,[2] it was the consensus of opinion in the discussion that followed that the possibility of error from this source is of negligible consequence in a field presenting so many difficulties a heterochromatic photometry, and that the effective check on these and many other points which were raised by us at that time—in addition to those now raised by Dr. Johnson—must come in comparison of the results with those obtained by the equality c brightness method. Because of this confirmatory opinion of a group of specialists fully familiar with all the technical and working detail of photometry and because of the check experiments we had run o the point to convince ourselves of the negligible influence of th factor for the conditions under which we worked (see this pape p. 165), we had not considered it necessary to raise the discussio in the preliminary exposition of the principles on which the pro posed method is based, contained in the article in question. How ever, since the point has been raised by Dr. Johnson, the followin comments may not be out of place.

[1] It is assumed here of course that Dr. Johnson referred to the angle for the colorl light. There can have been no reasonable doubt in his mind that the colored light w not obtained from the naked carbon or tungsten lamps to which his comments distribution refer. (See footnote, original article p. 9).

[2] With reference to the foregoing point and to others taken up in this discussion is scarcely needful to state that principles and descriptions of conditions of a techni nature were taken up in a fuller and more detailed way when a statement of the meth was presented to auditors technically interested in photometry than was done in t article criticized by Dr. Johnson.

(*a*) A general statement of the type which Dr. Johnson has made about the inequality of distribution of carbon and tungsten lamps is incomplete to the point of being somewhat misleading. As is well known, the distribution curve of an incandescent filament lamp depends upon the shape of the filament. While, for example, the single oval filament of the ordinary carbon lamp gives considerable unevenness of distribution, if wide enough angles are considered, the single loop tungsten filament of the Mazda lamp, series type, gives a curve which deviates so little from

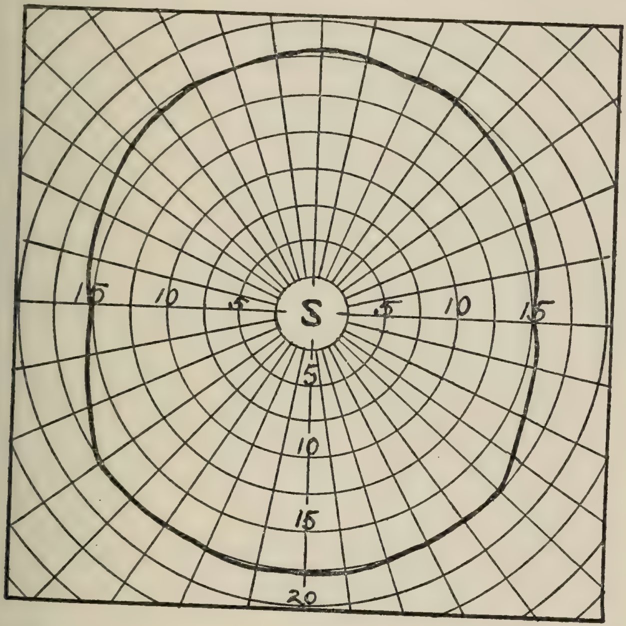

FIG. 1. Showing the distribution curve in the horizontal plane of a 50-watt arbon lamp, single oval filament—readings taken at 5 ft. radius; lamp operated at .8 horizontal cp.; watts per horizontal cp., 2.97.

circle as to be scarcely detectable with the exception of a very mall region in the plane of the filament. The curves for these amps are appended in Figs. 1 and 2. In Fig. 3 is given also the urve for the ordinary type B Mazda lamp.[1] This curve shows nore variation than the series lamp but it is so nearly uniform as o be considered circular for practical purposes. However, neither his nor the single oval filament carbon lamp have ever been used

[1] The determinations represented in these curves were made by the photometric boratory of the General Electric Co., Schenectady, N. Y.

by us in connection with the method of photometry in question without some device to secure greater uniformity of distribution of light. In case a naked lamp were used at all it has always been of the series type, single-loop tip-anchored filament, and care has been taken to have the lamp set on the bar so that the light was taken at right angles to the plane of the filament or from the most uniform part of the curve. But even were a carbon lamp used and the arrow

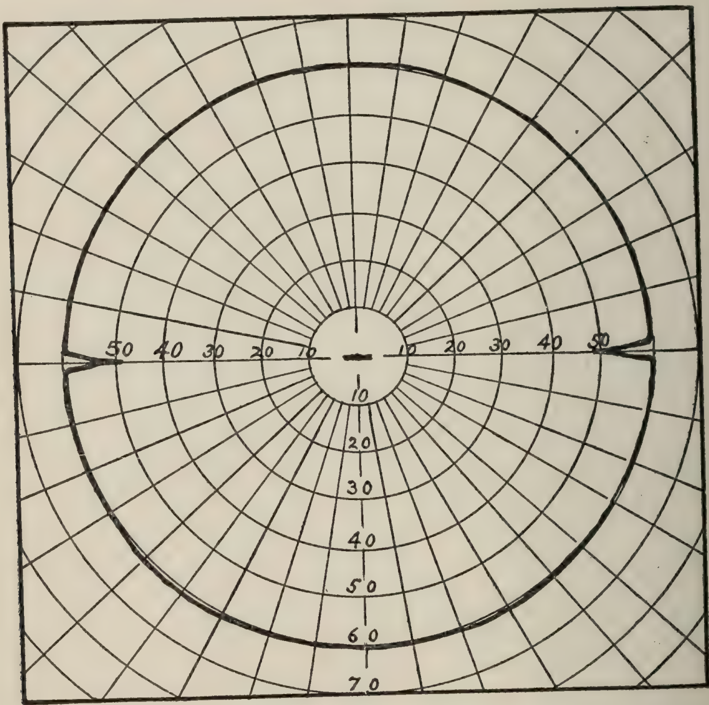

FIG. 2. Showing the distribution curve of a 60 cp. series Mazda lamp (clear) single loop tip anchored filament, 6.6 amps.—readings taken at 5 ft. radius; lamp operated at 60 horizontal cp.; watts per horizontal cp., 1.18.

or 'fiducial' mark scratched in a plane at right angles to the plane of the filament, the distribution would fall off so evenly on either side (see Fig. 1)[1] that the difference in the illumination of the stimulus patch and measuring disc, not exceeding 5.5° on either side, should be negligible.

[1] It should be noted that in making the cuts for the curves in Figs. 1 and 3 the true deviations from uniformity have been exaggerated by small but considerable amounts.

(*b*) So far as the question of uniformity of angular distribution of light is concerned, stress seems to be laid in the criticism on the equality of illumination of the stimulus patch and the measuring disc alone from the lights to be photometered. This is not at all in keeping with a correct interpretation of the method, for the photometric balance does not consist in the judgments of the actual amounts of light falling on the stimulus patch and measuring disc.

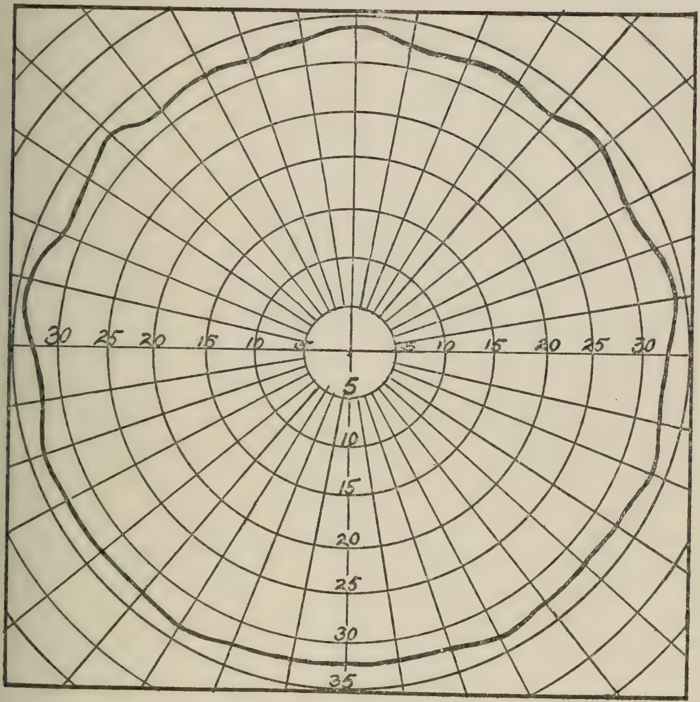

FIG. 3. Showing the distribution curve in the horizontal plane of a 40-watt G. E. Mazda lamp (clear), regular type small bulb, 110 volts—reading taken at 5 ft. radius; lamp operated at 32.5 horizontal cp.; watts per horizontal cp., 1.23.

The apparent brightness of the stimulus patch is, for example, the result of three factors: the actual amount of light falling on the stimulus patch, the amount falling on the surrounding screen (rather in both cases the amount reflected to the eye), and the physiological induction caused by the difference in the brightnesses of these two surfaces. Dr. Johnson, however, as indicated above, in considering the question of the distribution of the illumination and its probable effect on the results of the method, seems throughout his discussion

to take into account only the relative amounts of light received by the stimulus patch and the measuring disc, and in so doing shows a fundamental misunderstanding of the principle on which the method is based. The illumination of the field *surrounding* the stimulus patch is just as important as the illumination of the stimulus patch itself, for it is an equal factor in producing the induction and is, so far as any one knows, effective for induction up to the measuring disc; and there is, it is scarcely needful to point out, not an *angular separation of 15°* between this screen and the measuring disc. The important point is rather that there shall be no effective difference in the collective situation influencing the induction and its measurement for the standard and the comparison lamp. That is, although the two surfaces are compared in each judgment, the comparison of the two light sources is based on the results of two judgments, and if there is no difference in the collective situation influencing the two judgments, no injustice is done to the lights compared. If, therefore, we were considering with Dr. Johnson the relative illumination of stimulus patch and measuring disc to the exclusion of other factors, and to what degree this relative illumination is influenced by the distribution curve of the light source, the important item is not that there *is* an angular separation between them of a given number of degrees and a possible difference of illumination in consequence, but *how much this varies* for the position of the standard and comparison lamps on the photometer bar. For the nearest position of the standard lamp, the difference in the angular separation for the two lamps was 11°; for the farthest position for the distances as given in the table, the difference would have been 4.5°. However, for the greater distances that would have been required for the standard lamp from the screen to establish a balance with the less intense colored lights, a part of the reduction was produced by sectored discs, because in the form and set-up of apparatus employed for that work, distances of light from screen of 134–160 cm. (Table I., original article, p. 9) could not conveniently be attained owing to the angle of the shadow cast by the observer's head. This reduction was converted into terms of the law of squares to make the results comparable in the table with those obtained by the equality of brightness method. The actual setting of the lamp on the photometer bar for the greatest of these distances was 104 instead of 160 cm. The difference between the angular separation of stimulus patch and measuring disc was in this case therefore, 7°. The actual range of variation of angular separation

of stimulus patch and measuring disc was thus only from 7° to 11°. There is, it is obvious, considerable difference between these values and the 15° with which Dr. Johnson confronts us. Furthermore, in the course of the original work we ran a series of check experiments to determine whether this difference in angular separation in case of the standard and comparison lights produced any significant error. That is, in these check experiments both lights were kept in the same position and the light for the more intense, the standard, was reduced by means of sectored discs very accurately cut from sheet aluminum, the open sectors of which were measured with a protractor provided with a Vernier scale reading to minutes. The results of these experiments are given in Table I.

Table I.

Showing a Comparison of the Results Obtained for the Lights Represented in the Original Table when the Photometric Balance was made (*a*) by Changing the Setting of the Lights on the Photometer Bar; and (*b*) by the Use of the Sectored Disc

Source of Colored Light	Color	Distance of White Light Giving Equality of Illumination, Cm.	Ratio of Candle-power. Color: White	Value of Open Sector Giving Equality of Illumination with Distance of White and Colored Lights Equal	Ratio of Candle-power. Color: White	Difference in Ratio	Difference in Per Cent. Candle-power
87 cp. 41 cm. distant from photometric screen	Red	66.6	0.379	137.5°	0.382	0.0030	0.785
	Blue-green	59.5	0.4748	172.0	0.4778	0.0030	0.628
52 cp. 38 cm. distant from photometric screen	Red	82.2	0.2137	77.75	0.2160	0.0023	1.06
	Blue-green	70.5	0.2905	105.5	0.2931	0.0026	0.887
13 cp. 38 cm. distant from photometric screen	Red	160.0	0.0564	20.5	0.05694	0.00054	0.948
	Blue-green	134.9	0.0793	28.85	0.08014	0.00079	0.985

Moreover, so far as inequalities of illumination of stimulus patch and measuring disc are concerned, we may point out that a naked lamp was not even used in the experiments the results of which are given in the original table. Partly because the colored light was secured by means of colored filters, and partly as a precaution against unevenness of illumination of stimulus patch, measuring disc, and surrounding field for a height and breadth sufficient for the purpose of the experiment, the light was placed in a lamp-house

(see original article, footnote p. 9).[1] This lamp-house was 24 cm. high, 14 cm. wide and 14 cm. deep. At the lower end of the lamp-house was an opening 5 cm. square through which the light passed to the screen. The lamp-house was lined with mat white paper so shaped as to round off the edges and corners and to give as much as possible in the lower part of the enclosure the effect of the segment of a sphere. No light passed directly from the lamp to the screen as the tip of the lamp was for the different lamps used from 2 to 9 cm. above the opening for the emission of the light. Owing to the high absorption of the Wrattan and Wainwright filters the light from the lamp used to establish a balance with that transmitted from the filters had to be greatly reduced at the opening of the lamp-house by means of colorless absorbing screens, which served further to diffuse the light. To determine whether or not any serious difference in the distribution of light to measuring disc and stimulus patch was present in case of this device, the light was photometered at stimulus patch and at measuring disc for each position of the lights on the bar. No difference could be detected for these two positions by the equality of brightness method. Also the distribution curve for the light coming through this opening was found to be circular through an angle greater than the 11° in question. Our statement in the original article then was correct that the equality of distance of the measuring disc and stimulus patch on either side of the photometer bar guaranteed that they receive equal illumination from the light source employed. It would also be true within any reasonable margin of error for the single loop filament series lamp set as described above (without a lamp house), and even for the single oval carbon filament within a margin of error quite acceptable for work in heterochromatic photometry.

3. In a later paragraph (p. 394) Dr. Johnson conveys the impression that we claim an agreement between the results of the new method and those of the equality of brightness method within

[1] The lamp-house is not shown in the photograph of apparatus given in the original article. The photograph was a part of the general description of the method and the apparatus that might be used with it. In making this photograph the apparatus was regrouped, the object being merely to show the type of bar used, the screen and the measuring disc. In this photograph it will also be noted that the apparatus was not even shown in the position in which it is used in making the determinations. The use of a lamp-house is mentioned in another part of the article, namely the part treating of the results that were given as a sample of what might be obtained with the method. In the first photographs that were made the lamp-house was included, but its size and position in the foreground made it appear so disproportionately large that it was decided to omit it and to give the photograph the general character mentioned above.

a fraction of one per cent.[1] Of this we have to say that no numerical value whatever was assigned to the agreement in the original article nor was any general statement made that would warrant the inference that we claimed an agreement within so small a margin. All that appears in the article in this connection is a very brief table of results containing no reference whatever to the point in question accompanied by an 8-line paragraph stating that the table is appended as a *sample* of the results obtained, that the results are averages from 25 determinations, etc. It is the custom in photometry when a numerical expression is made of agreements, mean deviations, etc., to give these in per cent. illumination or per cent. candlepower. When this is done for the table in question, the agreement shown by the data given falls within 1.5 per cent. instead of 'within a fraction of 1 per cent.' as is stated by Dr. Johnson. And this it will be remembered, is an agreement in the average. When the individual determinations are compared, the deviations reach values of the order of + 10 and − 12 per cent. Some idea of this may be had from an inspection of the per cent. mean variations appearing in the table for the results obtained by the equality of brightness method. Thus it will be seen that the actual closeness of agreement of results is not surprising. It has been made to appear so only by our critic's method of presentation.

[1] On p. 393 Dr. Johnson says: "The authors do not describe their mode of procedure in making their measurements by the method of direct comparison. I assume, therefore, ... Under these conditions and working with the lamps beyond certain minimal distances from the photometer head, the luminous intensities of the compared sources would be *inversely* [italics ours] as the squares of their distances from the photometer screen at valid settings for equality of brightness on the two halves of the photometer field." We did not suppose that in an article on photometry it was necessary to give a description of the equality of brightness method over 100 years after its principles were laid down for all time (Pierre Bouguer, 1760, and Sir Benjamin Thompson, Count of Rumford, 1793). However, we do wish to say now that Dr. Johnson has raised the question that we conformed to all that is essential in his very elementary directions with the exception that we chose rather to follow the custom to which we know of no exception either in practice or recommendation, of calculating the luminous intensities of the light sources on the basis of the *direct* squares of the distances of these light sources from the photometer head, instead of the *inverse* squares. In replying to an advanced criticism on photometric method, one should not have to point out that the law of inverse squares applies to the intensity of illumination at different distances from a given source; while the converse of this relation, namely, the direct squares, applies to the comparative intensities of two sources which produce equal illumination on a given screen or photometer head. That is, the former is used in the computations of intensity of illumination: foot-candles, meter-candles, etc.; and the latter in the computation of the relative intensities of light sources: candlepower, lamberts, millilamberts, etc.

4. Also on p. 394 Dr. Johnson presents a table in which it is represented that the measuring disc in the work for which our table of results was submitted was 3 cm. nearer to the observer than the plane of the screen containing the stimulus patch. Applying the law of inverse squares he demonstrates that the illumination of the stimulus patch and measuring disc was in case of each light source unequal. Since the colored lights were all nearer the screen and measuring disc than the standard white light in proportions varying from 41 /59 to 38/ 160 (actually 41/ 59 to 38/ 106 because, as stated earlier, a sectored disc was used for the lights requiring the greater distance of setting from the screen), the 3 cm. caused a greater difference between the illumination of the measuring disc than of the stimulus patch for the colored lights than for the white light by percentages ranging from 5.4 to 15.5. From the showing of this table without further inquiry into causes, it was concluded that 'the authors' procedure in making the settings was faulty,' the 'method is insensitive' and that the evidence of agreement of the two methods is 'spurious,' for the explanation of which latter point there seems to have been no hypothesis worthy of mention but that the settings of one method were biased by a knowledge of the settings of the other—a smashing and uncompromising arraignment truly! However, we beg in passing to say a word of this table ourselves. In the first place, as a matter of only minor consequence to the present discussion, we wish to point out that in all of the computations given by Dr. Johnson of the deviations in per cent. from proportionality of illumination of stimulus patch and measuring disc, errors have been made, and that in 5 out of a total of 6 cases appearing in his table these errors have ranged from 1.8 to 11 per cent. of the correct value, with a leaning in some of the most important cases towards the advantage of the critic. This, we may be pardoned for noting, is under the circumstances somewhat surprising, and is of value perhaps chiefly in demonstrating that it is possible for mistakes to occur even in a critique levelled at the accuracy of the work of others without furnishing a justification for the impugning of motives and integrities. And secondly we wish to state that, as might have been suspected by our critic himself,[1] the 3 cm

[1] The above statement is made for the following reasons. (*a*) It is obvious on *a priori* grounds to one having even the least rudimentary knowledge of the principle on which photometry is based, that a just balance could not be established between th colored and white lights involving so wide a difference in setting on the bar if th measuring disc was 3 cm. in front of the photometer screen. And (*b*) even an approx mate set-up of the apparatus with the lights in position demonstrates at a glance tha

was a typographical error. In the original data still in our possession, the distance of the measuring disc from the screen is given as .3 cm.[1] When the law of inverse squares is applied to this, the discrepancy of illumination of stimulus patch and measuring disc for the distances used by Dr. Johnson in his computations ranges from .464 to 1.22 per cent., and for the actual distances used, from .464 to 1.03 per cent.—an amount which the experienced photometrist will, we think, grant is relatively negligible among the much greater sources of error present in heterochromatic photometry.

We have, however, been sufficiently curious to know what results would be obtained with the measuring disc placed 3 cm. in front of the screen to repeat the work represented in the original table for the four highest intensities with this change in the set-up. Differences from the results quoted in the original tables—also, as it happens for the cases tested, the amount of deviation from agreement with the equality of brightness results—ranged from 13.5 to 25 per cent. when the determination was begun with the weaker light, and from 18.6 to 29 per cent. when the determination was begun with the stronger light.[2] These figures indicate that rather than being remarkable for its insensitivity, as is charged by Dr. Johnson on the basis of too narrow a consideration of possibilities and apparently no first-hand knowledge whatever of the facts in question, the method shows by still another test a very high degree of sensitivity.

5. The error in our critic's final conclusion (pp. 395–6) should by this time be so obvious as to need no comment. We will, therefore, rest our case so far as we recognize that a case has existed, until space can be had for a further presentation of results. In this regard it is hardly necessary to mention that we do not consider,

the conditions produced are not compatible with the principles on which the method of making the balance is based. For example, when illuminated directly from the lamp on the bar a sharp shadow is cast by the disc on the screen, which is plainly in the view of the observer at the angle at which the observation is made. This is the equivalent of surrounding the disc with a black band which varies in width as the position of the lamp on the bar is changed. This is obviously not permissible. In fact the error is of a kind which is usually handled in a note of inquiry to the authors.

[1] Also there are, we might mention, a number of witnesses to the set-up of the apparatus used by us in the work on heterochromatic photometry.

[2] On account of the limited space allowed, an explanation of why such excessive deviations are obtained with this incorrect set-up will have to be deferred until later work; also the very obvious explanation of why a greater distance of measuring disc from screen was permissible, in fact of advantage, in the work in which the method was used to detect changes in the diffuse illumination of an optics-room (PSYCHOL. BULL., 1913, **10**, p. 371) than when it was applied to the rating of lights on a bar.

as our critic seems to have thought, that a place has been won for our method among those hoary and worn with service on the basis of a single sample table appended to a preliminary description of method and apparatus and representing the results of only one observer for two colors and only six of the possible settings on the photometer bar.

Note.—Dr. Johnson mentioned the use of a rotator to equalize the light radiation in different directions; also the deviations found by Wright from Lambert's law of reflection for mat surfaces. Since neither of these points was raised in the original article, it might be inferred that they were not known and taken into account by the authors. It will probably not be prejudicial to either side of the case to mention here that one of the writers supervised the construction of his first lamp rotator for work in photometry in 1901 while a teacher of physics, and is well acquainted with the uses and need of a rotator. Also in 1903 while a graduate student of physics he was assigned a study of the reflection from mat surfaces as a problem for investigation, the object being to continue along the lines mapped out by Wright. Both from his reading and instruction with regard to the work of Wright and others, however, he is totally unable to concur in a single comment that Dr. Johnson has made on the subject of diffuse reflection in the footnote on p. 392. Dr. Johnson says: "Another source of error which the authors appear not to have taken into account may be worthy of mention. The angles at which the light was diffusely reflected into the eye from the stimulus patch and the disc at the fixation point were not the same. The *percentage* of incident light reflected into the eye would have been different, therefore, even if the two surfaces had been of the same material. Furthermore, the difference in *percentage* of incident light reflected in the direction of the eye is not constant for any two positions of the source. Cf. Wright, H. R., 'Photometry of the Diffuse Reflection of Light on Matt Surfaces,' *Philos. Trans.*, 1900, **49**, Ser. 5, pp. 199–216." Of the sentences quoted the second is the only one that can be said to be true. The angle of emission *e* from the stimulus patch in relation to the eye was approximately 0°; while for the measuring disc it was 25°. The reflection, therefore, in the direction of the eye from a given point or unit surface in the area fixated of the measuring disc was less than that from the stimulus patch by an amount equal to the cosine of 25°. Dr. Johnson, however, neglects to take into account in considering the case presented by our method that the observation is not confined to a single point or unit of area and that the area of surface viewed increases as the secant (the reciprocal of the cosine) of the angle at which the surface is viewed measured from the normal. That is, the increase of the area viewed just compensates for the lessened amount of reflection from unit area. Nutting, for example, says: "A red hot metal plate is of the same brightness viewed at any angle since the foreshortening of the area just compensates for the variation in the radiation from a given area. Lambert's law holds for mat surfaces for both emitted and reflected radiation." Even the author referred to by our critic, in discussing the two possible methods of making the photometric determination in his investigation of the reflection from mat surfaces, says in effect the same thing (*cf.* Wright, p. 205), so without exception does every other author after whom we have read. Therefore when two mat surfaces are observed whose areas are not limited, the apparent brightness of these surfaces is the same for different angles of observation provided that the angle of incidence and amount of incident light are the same for both surfaces as was the case for the stimulus patch and measuring disc in our work for any one setting of the light on the bar; for

although the reflection from unit area decreases as the cosine of the angle of reflection, the area from which the eye receives its light increases as the secant of the same angle; from which it follows that the amount of light entering or reflected in the direction of the eye is independent of the angle at which the surface is viewed.

It is obvious, then, that Dr. Johnson's statement that the *percentage* of incident light reflected in the direction of the eye would have been different, even if the two surfaces had been of the same material, is not true. From this it is equally obvious that his next statement also is not true, namely, that the *difference* in the *percentage* of incident light reflected in the direction of the eye is not constant for any two positions of the source, for as shown above there is no difference in the *percentage* of incident light reflected to the eye from the two surfaces for any given setting of the light on the bar. In other words, the possible bearing of Lambert's law and Wright's results with regard to this law, is not what Dr. Johnson has stated it to be. Just what this bearing is will be discussed further on in this note. What we wish to do at this point is to show that even if it were true that the percentage of incident light reflected to the eye were different for any one setting of the light on the photometer bar, this would make no difference whatever in the results obtained by our method. That is, if less light were reflected to the eye from the measuring disc than from the stimulus patch for the first light set upon the bar, it would mean merely that the coefficient of reflection of the measuring disc would have to be reduced by a corresponding amount to obtain the match. Then when the comparison light was placed on the bar and its distance adjusted until as much light was given to the screen as was received from the first light, the stimulus patch and measuring disc would again match, for neither the difference in angle of reflection to the eye nor the reflection coefficients would have been changed. Dr. Johnson's point, granting its verity, would have application only if the stimulus patch were illuminated alone by one of the lights and the measuring disc by the other and the method of balancing consisted in bringing these two surfaces to equality—then it would be necessary that each reflect to the eye the same percentage of the light received by it; but the point is clearly quite irrelevant to the method described by us in which the two surfaces are illuminated for each judgment by only one of the lights, and the balance consists in so adjusting the distance of the two lights in the successive judgments that the match for the one based on the amount of induction produced at the stimulus patch holds also for the other. In this case it is important only that the physical situation and other factors be kept the same for both judgments—not that they be equal each to each for the single judgment—for the balance is based on the principle that if all the factors are kept constant the amount of induction at the stimulus patch will always be the same when the same amounts of light are received on the screen. It is obvious also that the same considerations are true with regard to the materials forming the stimulus patch and measuring disc. Moreover, with reference to this point, it may also be said that there was, as a matter of fact, very little difference in the materials forming the two surfaces; for one sector of the measuring disc was identical with the stimulus patch and the other sector was a darker gray of the same series of papers (Hering's series of standard grays).

In concluding our comments on this footnote which has revealed so much of our critic's point of view, we will indicate briefly and only in a general way the relation of Lambert's law of reflection from mat surfaces and Wright's findings with regard to this law to the practical working of our method. As already shown, Dr. Johnson's criticism was based both on an erroneous understanding of this law as applied to the making of the photometric judgment by any method whatsoever and on a wrong conception of

the principles of the method criticized. Our actual chance of error in terms of Lambert's law is that the *angle of incidence* (Johnson's 'difference in *angle of reflection*' has nothing whatever to do with photometry from mat surfaces) on the stimulus patch and its surrounding field is different for the light from the standard and comparison lamps when they are of different intensities and a different setting on the bar is required to establish the photometric balance. That is, according to Lambert's law the intensity of the illumination of the stimulus patch and its surrounding field is proportional to the cosine of the angle of incidence (the cosine i).

Now considering for the sake of simplicity the stimulus patch alone, the variation in the cosine of the angle of the incident light for the entire range covered in the work criticized from the least to the greatest distance of the source of light from the screen, falls within 1 per cent. While this would mean only a comparatively slight difference in the induction situation from the lights compared, we have from the beginning in our own thinking frankly faced it as a small source of error in case the reductions of the light on the screen are produced by changing the position of the lamps on the bar. However, it would not enter in at all, as will be readily seen, if the reduction of light is produced by means of a sectored disc or any device: absorbing screen, Nicol's prism, grating, etc., which does not change the distance of the source of light from the screen and, therefore, the angle of incidence of the light on the stimulus patch. In this regard it should be remembered too that our photometer is no more at fault in physical principle than the equality of brightness photometer after Rumford as ordinarily constructed, in which also the angle of incidence is changed with a change of the position of the light on the bar—not so much at fault perhaps, for compensating factors operate in our method of getting the balance which are not present in the Rumford method. The relation of Wright's results to the situation described here is that he found that there are certain small deviations from the law of the cosine i as the angle of incidence is changed. Now just how great the chance of error is in our method from the law of the cosine i considered in relation with the results of Wright it is utterly impossible to estimate with any acceptable degree of precision from the principles involved for the following reasons: (*a*) The surrounding field as well as the stimulus patch must be taken into account in applying the law of cosines. The difference in the angle of incidence for the different points in this field vary for any two positions of the light on the bar—towards zero as a limit, for example, for the points between the stimulus patch and the end of the bar, and differently in other directions. (*b*) The effect is not direct but operates through induction, the quantitative relations of which are not definitely known. And (*c*) Wright apparently considered it worth while to make no change of angle of incidence smaller than 20°, while the entire range of variation of this angle in our work from greatest to least distance of lamp from screen was for the colorless light 2° and for both the colored and colorless lights 5°.

Rather, therefore, than indulge in bootless speculation in regard to the possibilities of error from these sources, it is obviously much more to the point to get some empirical measure of their effective importance. The effective importance of this factor along with others not mentioned by Dr. Johnson may be checked up (*a*) by a comparison of results in the average with those obtained by the equality of brightness method (see table in original article, p. 9); and (*b*) still more definitely and directly by comparing the results obtained by the method when the reductions of the light on the screen are produced by changing the distances of the sources from the screen and when the distance of the source and, therefore, the angle of incidence of the light is kept constant and the reductions are made by means of a sectored disc (see Table I. of this discussion).

Even had these comparisons not been made, the probable relative unimportance of these sources of error as compared with the high variable error obtained for one or any small number of determinations by the equality of brightness method, should, we think, be obvious to all who have a working familiarity with the latter method in heterochromatic photometry. On the point of sureness of principle, moreover, it is instructive to compare the agreements of the induction and equality of brightness methods shown in the tables referred to above with those obtained for the equality of brightness and flicker methods, for example, for lights presenting the same amount of color difference.

Bryn Mawr College,

C. E. Ferree,
Gertrude Rand.

[The above discussion, which exceeds our usual limits, has been accepted by the Editors in order that the authors might have ample opportunity to clear up the points raised in Dr. Johnson's Note. The questions at issue are so specialized and technical that we believe it unprofitable to continue the discussion in the pages of the Review. A committee of experts acceptable to both parties may be suggested as the best means of settling any differences which remain between the writers and their critic.—The Editors.]

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A NOTE ON THE NEEDS AND USES OF ENERGY MEASUREMENTS FOR WORK IN PSYCHOLOGICAL OPTICS

A BRIEF discussion of this subject was given by us five years ago in an article, entitled "A Note on the Determination of the Retina's Sensitivity to Colored Light in Terms of Radiometric Units."[1] Since that time some dispute has arisen with regard to the comparative merits of the subjective and objective types of measurement of the stimulus light for work in psychological optics. Time alone can, of course, reveal the full range of needs and uses of the objective type of measurement. A few words in the way of general perspective, however, may not be out of place at this time.

Considered in its relation to the eye, two points of view may be recognized in the rating of lights. One of these is involved in their rating for the use of the eye as an organ of seeing. In such a rating it is obvious that the method should take into account all of the eye's peculiarities of response to the different wave-lengths of light. In the production of illuminating effects this is the work of photometry, which should be done by the eye or some instrument calibrated to give results in terms of the responses of the eye. Another and quite a different point of view, however, is involved in their rating for the purpose of investigating the eye's peculiarities or characteristics of response in every way in which it is capable of giving response. In such work it is obvious that the ultimate method of making the rating should be free from the peculiarities to be investigated, that is, should not be made by the eye itself. In general, in work of this kind, two needs arise. (1) A method of specification is required which will make possible an accurate and convenient reproduction of intensities from time to time and from laboratory to laboratory. The difficulty of doing this by photometry with lights differing widely as to wave-length, as do in most cases the stimuli employed in psychological optics, is too well known to need emphasiz-

ing here. Obviously what is needed for certitude in this work, is a measuring instrument which can be calibrated directly against th standard of radiation, or black body, and which is non-selective i its response to wave-length—not an instrument like the eye, th selenium cell, the photo-electric cell, or the photographic plate, th responses of which are not only selective to wave-length, but var in their amounts of selectiveness with change of intensity of light differ greatly in both of these regards (especially the eye) from instrument to instrument or from sense organ to sense organ, an can not be calibrated against the total of radiation of a black body

The insistence on a subjective method of rating for standardiz ing purposes, when the objective method is available, is not onl difficult to understand, but is entirely contradictory to current prac tise in other sense fields. No one would think, for example, o specifying, for the purpose of securing reproducibility, the weight used in an investigation of skin sensitivities in terms of the skin own responses when the means of making the physical measuremen is at hand; yet there should be more chance of successfully estab lishing from laboratory to laboratory a system of calibration of ski measurements in terms of some common standard than there is o accomplishing the analogous task in case of light. It is scarcel conceivable that the most ardent advocate of subjective ratings i case of light would recommend the substitution of the subjective fo the objective method for work on the skin for the simple reason tha it would be so undesirable as not to be tolerated unless, for wan of an objective method, it was rendered absolutely necessary. Wit the objective method available from the beginning, the possibility o using the subjective method has not even been raised in work on th skin. And indeed the subjective method has been used in ratin light intensities only because (*a*) for more than a hundred years n other method was available, and (*b*) it was desirable to rate ligh for use in seeing by a method which gave results corresponding the eye's powers of response. The former of these reasons for i use has now disappeared. Only the latter, with a few laborato exceptions, remains and marks off for the subjective method rating a separate and special field which is clearly recognized such by physicists and the engineers dealing with the problem lighting.

As a brief, however, for the continuation of the use of the e for the measurement of its own stimuli, although such measureme would not be subjective, it may be claimed that in time it will possible to calibrate the eye by means of the non-selective radio eters so that it can be used to measure the visible energies direct For example, just as it is possible to measure a linear dimension wi

a meter rod and to convert the results into terms of the English system, and *vice versa;* so it may be possible to measure the different wave-lengths of light by the eye and convert the results obtained into energy values. The difficulties in the way of this, as we have already pointed out, consist in differences in the sensitivity of different eyes for a given wave-length; the selectiveness of the eye's response to wave-length and to intensity and its variations in both of these regards from observer to observer; the lack of a fixed scale from observation to observation, even in the case of a single observer, *etc.* In short, to complete the analogy suggested above, it would be an exceedingly difficult task to convert measurements from the metric into the English system and *vice versa* if very few of the measuring rods employed represented the same amounts of linear space; if in case of a given rod the dimensions of some objects were underestimated and others overestimated and the magnitude of this underestimation and overestimation varied with the dimensions of the object measured by amounts as yet undetermined, *etc.,* as happens in case of the eye's evaluations of the wave-lengths of the visible spectrum. Obviously if the eye's ratings are to be converted into energy values, this conversion can come only after a very great deal of investigation and calibration against radiation standards by means, for example, of the non-selective radiometers, which but constitutes one of the subdivisions of what we have included under the second of the needs we are giving for energy measurements in the study of the responses of the eye. However, to represent the calibration as now completed and available for use instead of scarcely begun, as is being done in some quarters, is chimerical and visionary to a degree which we can consider compatible only with an inadequate knowledge and understanding of all that is involved in the problem.

(2) The second and perhaps more fundamental need for energy measurements for work on the eye is, as stated in the general heading, for a method of rating the stimulus which will make possible a quantitative comparison of the eye's power of response to its stimuli in every way in which it is capable of giving a response; for we can know the kind and amount of its selectiveness of reaction to the different wave-lengths of light only when they are compared with those of an instrument as a standard which shows equal power or capacity of response to all wave-lengths. Only with such an instrument, or rather with such an evaluation of the stimuli as a common and invariable standard to which to refer the eye's evaluations or responses, can the work of comparing its powers or peculiarities of response to its stimuli be put on a basis that can be called quantitative for a single eye or from eye to eye. To this it may be demurred, however, that in some problems it is required as one of the

features of the investigation that the stimuli have equal power t arouse the eye's response or sustain some subjective relation to each other. This need we have always freely recognized both in ou work and in our recommendations.[2] It in no way conflicts with however, or supplants the more fundamental one already given, but is rather supplementary to it in certain types of investigation; fo even in the cases where the subjective relation is demanded t fulfil the requirements of the investigation there is still great nee for the ultimate purposes of the science that the physical amount of light required to produce this subjective relation for the give observer be determined and specified. Again to use the analogy o work on skin sensation, it would be a careless investigator indee who would fail to specify, if it were possible to do so, the physica measure of the weights he used to give equal pressure responses for example. In short, it seems a paradox that one should even fee the need to make a special pleading for the introduction of ob jective measurements into the work of psychological optics when i is the current practise to use objective ratings of the stimulus i every other field of psychological investigation in which it is possibl to do so, the intensity ratings in vision and audition alone being th conspicuous outstanding exceptions and these being so only be cause adequate methods for making such ratings have been slow i coming.

As examples of needs for regulating the stimuli to give certai subjective relations we may quote here the following cases that w have already formally recognized. In a recent investigation o the comparative lags of the achromatic response to wave-lengt made in our laboratory, the stimuli employed were made phot metrically equal and the amounts of light used to give these equa responses were measured radiometrically. The photometric equaliz tions were made because the data were wanted in an interpretatio of the characteristic overestimations and underestimations found i the results of certain observers in photometry by the method c flicker as compared with their results by the equality of brightne method. In another case in a determination of whether stimu which have the same power to arouse the achromatic response hav also the same power to make the eye lose in its capacity to give th response as a result of prolonged stimulation, the stimuli were as matter of course made subjectively equal as one of the essenti conditions of the investigation; but again the amounts of light r quired to produce this subjective relation were determined radi metrically for the purpose of ultimate specification. Also in o

[2] See, for example, *American Journal of Psychology*, Vol. XXIII., p 329–331.

original note on energy measurements we recognized quite broadly the possible need of establishing subjective relations between the stimuli used. For example, in discussing methods of determining after-image and contrast sensitivity, we state: "It is conceivable that two points of view may be held with regard to what is meant by after-image and contrast sensitivity. (1) After-image and contrast sensitivity may express a relation between the amount of light required to arouse after-image and contrast sensations and the unit of light used. (2) It may express a relation between the amount of light required to arouse the after-image and contrast sensations and the amount required to arouse the positive sensation."[3] In the former case the after-image or contrast sensations are treated as one of the eye responses the selectiveness of which to wave-length is to be determined; in the latter a figure is sought which expresses the relation between the after-image and contrast and the positive sensitivities. On the same page and the one following we say: "Similarly, two views may be held with regard to the determination of the comparative rates of fatigue, and of the development-time of sensation. (1) Lights equalized in energy may be used. (2) The energy of the lights may be made proportional to the sensitivity of the eye to the different colors." Also in discussing the investigation of the peripheral limits of sensitivity, we state: "(*a*) The limits may be considered in relation to the comparative sensitivity of the retina to the different colors. (*b*) They may be considered in relation to existing color theories. In the first of these problems the limits should be obtained with stimuli equalized in energy. So obtained, the results will constitute merely another expression of the comparative sensitivity of the retina to the different colors." "The second problem is more complicated and will be made the subject of a separate paper." Indeed, as these citations abundantly show, we have never failed to recognize that the stimuli in certain types of investigation must be made to conform to some type of subjective relation, but these investigations constitute in immediate importance only a minor part of the work that is to be done in getting a thorough knowledge of the eye's characteristics of response; and even in these investigations there is as great need of an invariable standard of reference as there is in any field, psychological or otherwise, where the value of quantitative work or measurement is recognized.

Perhaps the general character of the discussion will not be deviated from too widely if we add in conclusion a word on the determination of retinal sensitivities which will indicate in a concrete case the type of treatment that should in our opinion be given

[3] *Op. cit.*, p. 329.

both to the response and to the stimulus, when possible, in quantitative work in psychological optics. If the sensitivity of the retina is to be measured in a way that is comparable with the measurement of the sensitivity of the physical recording instruments, two conditions must be fulfilled: (*a*) the amounts of response in terms of which the comparison is to be made must be numerically comparable; and (*b*) the amounts of stimulus used in arousing the response must also be numerically comparable or commensurable. The sensitivity of two galvanometers could not be compared, for example, were it not known that the divisions on the scale of each were either equal or commensurable; likewise the amounts of current used to produce the given deflections must be known in terms of the same or comparable units. With the introduction of the radiometric treatment of the stimulus the second of the above conditions is fulfilled, and for the first time in a way that can be considered quantitative to a degree that would be acceptable in rating the sensitivity of a physical instrument. With reference to the first condition we are confronted with a situation somewhat similar to that which obtains in heterochromatic photometry. That is, in general, five different quantities have been used or suggested in the work of measuring sensitivities (the liminal threshold, the just noticeable difference, the average error, equal amounts of response and equal sense differences), but only the last two of these conform to the requirement that is considered absolutely necessary in determining the sensitivity of a physical instrument, namely, that the amounts of response as well as the amounts of stimulus must be numerically comparable. Moreover, in the absence of sureness of principle in case of the other three, the empirical check of agreement in result with those that have the needed sureness of principle has never been offered; yet sensitivities are determined just as if this condition did not exist, comparisons are made and conclusions are drawn. In short it may not be out of place to call attention here to the looseness of thinking and practise that prevails more or less generally with regard to the work of determining physiological sensitivities as compared with the analogous physical determinations. For the sake of consistency it might well be urged either that this work be revised on the basis of the standards set for the physical instruments with all of the interchecking of methods that is needed, or that the term sensitivity with its definite quantitative connotation be abandoned in all cases in which this standard can not be lived up to.

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Radiometric Apparatus for Use in Psychological and Physiological Optics

Including a Discussion of the Various Types of Instruments that have been used for Measuring Light Intensities

BY

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PREFACE

Six years ago, realizing the fundamental relation of energy measurements to quantitative work in psychological optics, we undertook to procure a non-selective radiometer which not only would be sufficiently sensitive for work in the visible spectrum, but the operation of which would be within the technical possibilities of the laboratories in which research is done in psychological optics. At that time we decided upon an instrument of the surface type because (a) we wished to measure all of the light falling on the opening of our campimeter screen rather than compute it from several measurements with the linear type of instrument; and (b) we believed that sensitivity would be added to the instrument in some proportion to the increase in area of the receiving surface (see this paper p. 12). A quick acting surface thermopile, because of its superior steadiness and ease of operation, seemed to be best adapted to our purpose. Since such an instrument could not be obtained in the market, Dr. W. W. Coblentz of the radiometric division of the Bureau of Standards who had at that time just finished a comparative study of the radiometric instruments showing the above-mentioned advantages of the thermopile, undertook the design and construction of the thermopiles, surface and linear, and the auxiliary radiometric apparatus which we have used in our work. These thermopiles are the first of their type made by Dr. Coblentz (see Bulletin of the Bureau of Standards, 1913, pp. 15-29) and have been used by us for five years. Thermopiles of this type are now in use also in many physical laboratories and in other laboratories in which a sensitive and convenient means is needed for measuring spectrum energies.* We

*For example, the recent work of Nutting (Phil. Mag., 1915, *29*, (6), p.), Ives, Coblentz and Kingsbury (Phys. Rev., 1915, *5*, (2), p. 269), and Coblentz and Emerson (Bull. Bur. of Standards, 1917, *14*, p. 167), on the visibility of radiation and the mechanical equivalent of light, of interest to psychologists, has been done and was made conveniently possible by these improved thermopiles designed and constructed by Dr. Coblentz.

are not thus recommending in the following pages an apparatus the feasibility and convenience of which for quantitative work of the kind needed in psychological optics is untried.

Of late some dispute seems to have arisen with regard to th need and uses of energy measurements for work in psychologica optics. A brief discussion and statement of opinion on thi point was given by us in an article published in the America Journal of Psychology in 1912. (A Note on the Determinatio of the Retina's Sensitivity to Colored Light in Radiometri Units, 23, pp. 328-332.) Time alone can of course revea the full range of needs and uses of this type of measuremen and render a just verdict on disputed points. A few words i the way of general perspective, however, may not be out o place here.

Considered in its relation to the eye two points of view ma be recognized in the rating of lights. One of these is involve in their rating for the use of the eye as an organ of seeing. I such a rating it is obvious that the method used should tal into account all of the eye's deviations from equality of respon to the different wave-lengths of light. In the production illuminating effects this is the work of photometry which shou be done by the eye or some instrument calibrated to give resul in terms of the responses of the eye. Another and quite di ferent point of view, however, is involved in their rating f the purpose of investigating the eye's peculiarities or characte istics of response in every way in which it is capable of givi response. In such work it is obvious that the ultimate meth of making the rating should be free from the peculiarities be investigated, that is, should not be made by the eye itself. general in work of this kind two needs arise. (1) A method specification is required that will make possible an accurate a convenient reproduction of intensities from time to time a from laboratory to laboratory. The difficulty of doing this photometry with lights differing widely as to wave-length do in most cases the stimuli employed in psychological opti is too well known to need emphasizing here. Obviously w is needed for certitude in this work is a measuring instrum

which can be calibrated directly against the standard of radiation, or black body, and which is non-selective in its response to wave-length,—not an instrument like the eye, the selenium cell, the photo-electric cell, or the photographic plate, the responses of which are not only selective to wave-length but vary in their amounts of selectiveness with change of intensity of light, differ greatly in both of these regards (especially the eye) from instrument to instrument or from sense organ to sense organ, and can be calibrated against the radiation standard or black body, if at all, only with a great deal of difficulty and with many chances of cumulative error.

The insistence on a subjective method of rating for standardizing purposes when the objective method is available, is not only difficult to understand but is entirely contradictory to current practice in other sense fields. No one would think, for example, of specifying for the purpose of securing reproducibility, the weights used in an investigation of skin sensitivities in terms of the skin's own responses when the means of making the physical measurement is at hand; yet there should be more chance of successfully establishing from laboratory to laboratory a system of calibration of skin measurements in terms of some common standard than there is of accomplishing the analogous task in case of light. It is scarcely conceivable that the most ardent advocate of subjective ratings in case of light would recommend the substitution of the subjective for the objective method for work on the skin for the simple reason that it would be so undesirable as not to be tolerated, unless for want of an objective method it was rendered absolutely necessary. With the objective method available from the beginning, the possibility of using the subjective method has not even been raised in work on the skin. And indeed the subjective method has been used in rating light intensities only because (a) for more than a hundred years no other method was available, and (b) it was desirable to rate lights for use in seeing by a method which gave results corresponding to the eye's powers of response. The former of these reasons for its use has now disappeared. Only the latter, with a few laboratory exceptions, remains and marks

off for the subjective method of rating, a separate and specia field which is clearly recognized as such by physicists and th engineers dealing with the problem of lighting.

As a brief, however, for the continuation of the use of th eye for the measurement of its own stimuli, although such meas urements would not be subjective, it may be claimed that in tim it will be possible to calibrate the eye by means of the non selective radiometers so that it can be used to measure the visibl energies directly. For example, just as it is possible to measur a linear dimension with a meter rod and to convert the result into terms of the English system, and *vice versa;* so it may b possible to measure the different wave-lengths of light by th eye and convert the results obtained into energy values. Th difficulties in the way of this, as we have already pointed ou consist in differences in the sensitivity of different eyes for given wave-length; the selectiveness of the eye's response t wave-length and to intensity and its variations in both of thes regards from observer to observer; the lack of a fixed scale fro observation to observation, even in the case of a single observe etc. In short to complete the analogy suggested above, it wou be an exceedingly difficult task to convert measurements fro the metric into the English system and *vice versa* if very fe of the measuring rods employed represented the same amoun of linear space; if in case of a given rod the dimensions of son objects were over-estimated and others under-estimated and t magnitude of this over-estimation and under-estimation vari with the dimensions of the object measured by amounts as y undetermined; etc.,—as happens in case of the eye's evaluatio of the wave-lengths of the visible spectrum. Obviously if t eye's ratings are to be converted into energy values, it can co only after a very great deal of investigation and calibrati against radiation standards by means, for example, of the no selective radiometers, which but constitutes one of the su divisions of what we have included under the second of t needs we are giving for energy measurements in the study of t responses of the eye. However, to represent the calibration now completed and available for use instead of scarcely begu

would be chimerical and visionary to a degree which we can consider compatible only with an insufficient knowledge and understanding of all that is involved in the problem.

Since the foregoing was written, Troland (Journal of Experimental Psychology, 1917, *2*, pp. 7-13) has advised that, instead of the thermopile or other non-selective radiometer, the psychologist may, with sufficient accuracy for his purpose, use the eye as a selective radiometer and convert the results into units of energy by means of a value for the mechanical equivalent of light that has recently been determined by Nutting (Philos. Mag., 1915, *29*, (6), p. 301). This point can not be discussed here in detail. We would, however, recommend that the reader consult this work on the mechanical equivalent, which has been done by means of the flicker photometer and the thermopile, and judge for himself how unreliable it would be to attempt to follow Dr. Troland's advice and use a result obtained with a given limited group of observers for only one intensity of light, to convert the photometric results of individual observers in other laboratories and for other ntensities of light into anything at all closely approximating the correct energy values. It is obvious that in order to make the conversion in any given case with the same order of accuracy with which the direct energy neasurements may be made, the same observers would have to be used, the ame state of adaptation and sensitivity of the eye, the same intensity of ight or approximately so (at least so far as adequate proof to the contrary or a large part of the intensity scale is concerned), the exact same range of vave-lengths and distribution of energy within the group of wave-lengths, and he same degree of purity of light as were used in making the original de-ermination of the visibility curve which is meant to serve as the basis for naking the conversion. Considering the first of these points alone, it will be emembered that Ives, working through the spectrum with the flicker photo-neter, found in a group of eighteen observers disagreements as great as 159 er cent for .487μ; 114 per cent for .498μ; 26 per cent for .518μ; 18 per cent or .537μ; 13 per cent for .556μ; 10 per cent for .576μ; 28 per cent for .595μ; ; per cent for .615μ; 86 per cent for .635μ; and 122 per cent for .655μ. Philos. Mag., 1912, *24*, Ser. 6, pp. 856-863.) From this showing of low agree-ent from observer to observer with the flicker photometer, it is clear that the sults for individual observers could not be used for the purpose of making e conversions recommended unless some means were had of correcting these sults to those of the group for which the original visibility curve and the echanical equivalent were determined. Space can not be taken here to scuss the complications and approximations that would be involved in aking such a correction. It will be sufficient to say that if it were made the most approved manner—an adequate method of doing it has not by y means as yet been devised—and the mechanical equivalent were applied, results would scarcely be accepted as correct even by an ordinarily care-l worker unless they could be checked up by a direct energy measurement. this connection it is interesting and important to note that the visibility rve as determined by Nutting does not agree with that determined by es, also that the curves of Nutting and Coblentz agree only when certain

corrections are made in the energy measurements of Nutting. In short the attempt to get a set of figures that will express for the different wave-lengths the relation of the lumen as evaluated by a number of eyes to the watt is an interesting bit of work and may present, perhaps, when the proper computations are made, a rough analogy to the determination of the mechanical equivalent of heat; but the attempt to use these figures to convert the photometric results of the individual observers in the different laboratories into the correct energy values is quite a different matter, and can scarcely be considered as the intent of those who have made the determination. This question will be discussed in greater detail in a later paper.

However, the idea of using the eye indirectly to determine the energy values of light is by no means new. Before the direct type of measurement had been made as feasible as it now is, several attempts were made to use the eye for this purpose. (See, for example, Lummer and Pringsheim. Jahresber. d. Schles. Ges. f. vaterl. Kultur, 1906, pp. 95-97; Beibl., 1907, p. 466; Thürmel, Das Lummer-Pringsheimsche Spektral-Flickerphotometer als optisches Pyrometer, Ann. der Phys., 1910, *33*, (4), pp. 1139, 1160; etc.)

(2) The second and perhaps more fundamental need for energy measurements for work on the eye is, as stated in the general heading, for a method of rating the stimulus which wil make possible a quantitative comparison of the eye's power o response to its stimuli in every way in which it is capable o giving a response; for we can know the kind and amount o its selectiveness of reaction to the different wave-lengths of ligh only when they are compared with those of an instrument a standard which shows equal power or capacity of respons to all wave-lengths. Only with such an instrument, or rathe with such an evaluation of the stimuli as a common or invariabl standard to which to refer the eye's evaluations or responses can the work of comparing its powers or peculiarities of respons to its stimuli be put on a basis that can be called quantitativ for a single eye or from eye to eye. To this it may be demurrec however, that in some problems it is required as one of the fea tures of the investigation that the stimuli have equal power t arouse the eye's response or sustain some subjective relation t each other. This need we have always freely recognized bot in our work and in our recommendations. (See Amer Jour. of Psychol., 1912, *23*, pp. 328-332.) It in no way con flicts with, however, or supplants the more fundamental on already given, but is rather supplementary to it in certain typ

of investigation; for even in the cases where the subjective relation is demanded to fulfill the requirements of the investigation there is still great need for the ultimate purposes of the science that the physical amounts of light required to produce this subjective relation for the given observer be determined and specified. Again to use the analogy of work on skin sensation, it would be a careless investigator indeed who would fail to specify, if it were possible to do so, the physical measure of the weights he used to give, for example, equal pressure responses. In short, it seems a paradox that one should even feel the need to make a special pleading for the introduction of objective measurements into the work of psychological optics when it is the current practice to use objective ratings of the stimulus in every other field of psychological investigation in which it is possible to do so, the intensity ratings in vision and audition alone being the conspicuous outstanding exceptions and these being so only because adequate methods for making such ratings have been slow in coming.

As examples of needs for regulating the stimuli to give certain subjective relations we may quote here the following cases that we have already formally recognized. In a recent investigation of the comparative lags of the achromatic response to wave-length made in our laboratory, the stimuli employed were made photometrically equal and the amounts of light used to give these equal responses were measured radiometrically. The photometric equalizations were made because the data were wanted in an interpretation of the characteristic overestimations and underestimations found in the results of certain observers in photometry by the method of flicker as compared with their results by the equality of brightness method. In another investigation now in progress, namely, a determination of whether stimuli which have the same power to arouse the achromatic response have also the same power to make the eye lose in its capacity to give this response as a result of prolonged stimulation, the stimuli are as a matter of course being made subjectively equal as one of the essential conditions of the investigation; but again the amounts of light required to produce this subjective re-

lation will be determined radiometrically for the purpose of ultimate specification. Also in our original note on energy measurements we recognized quite broadly the possible need of establishing subjective relations between the stimuli used. For example, on p. 329 in discussing methods of determining after-image and contrast sensitivity, we state: "It is conceivable that two points of view may be held with regard to what is meant by after-image and contrast sensitivity. (1) After-image and contrast sensitivity may express a relation between the amounts of light required to arouse after-image and contrast sensations and the unit of light used. (2) It may express a relation between the amount of light required to arouse the after-image and contrast sensations and the amount required to arouse the positive sensation." In the former case the after-image or contrast sensations are treated as one of the eye's responses the selectiveness of which to wave-length is to be determined; in the latter a figure is sought which expresses the relation between the after-image and contrast and the positive sensitivities. On the same and the succeeding page we say: "Similarly two views may be held with regard to the determination of the comparative rates of fatigue, and of the development-time of sensation. (1) Lights equalized in energy may be used. (2) The energy of the lights may be made proportional to the sensitivity of the eye to the different colors." Also in discussing the investigation of the peripheral limits of sensitivity, we state: "(a) The limits may be considered in relation to the comparative sensitivity of the retina to the different colors. (b) They may be considered in relation to existing color theories. In the first of these problems the limits should be obtained with stimuli equalized in energy. So obtained the results will constitute merely another expression of the comparative sensitivity of the retina to the different colors. The second problem is more complicated and will be made the subject of a separate paper." Indeed as these citations abundantly show, we have never failed to recognize that the stimuli in certain types of investigation must be made to conform to some type of subjective relation, but these investigations constitute in immediate importance only a minor part of the

work that is to be done in getting a thorough knowledge of the eye's characteristics of response; and even in these investigations there is as great need of an invariable standard of reference as there is in any field, psychological or otherwise, where the value of quantitative work or measurement is recognized.

Perhaps the general character of the discussion will not be deviated from too widely if we add in conclusion a word on the determination of retinal sensitivities which will indicate in a concrete case the type of treatment that should in our opinion be given both to the response and to the stimulus, when possible, in quantitative work in psychological optics. If the sensitivity of the retina is to be measured in a way that is comparable with the measurement of the sensitivity of the physical recording instruments, two conditions must be fulfilled: (a) the amounts of response in terms of which the comparison is to be made must be numerically comparable; and (b) the amounts of stimulus used in arousing the response must also be numerically comparable, or commensurable. The sensitivity of two galvanometers could not be compared, for example, were it not known that the divisions on the scale of each were either equal or commensurable; likewise the amounts of current used to produce the given deflections must be known in terms of the same, or comparable units. With the introduction of the radiometric treatment of the stimulus the second of the above conditions is fulfilled, and for the first time in a way that can be considered as quantitative to a degree that would be acceptable in the rating of the sensitivity of a physical instrument. With reference to the first condition we are confronted with a situation somewhat similar to that which obtains in heterochromatic photometry. That is, in general five different quantities have been used or suggested in the work of measuring sensitivities (the liminal threshold, the just noticeable difference, the average error, equal amounts of response and equal sense differences), but only the last two of these, so far as has yet been demonstrated, conform with certainty to the requirement that is considered absolutely necessary in determining the sensitivity of a physical instrument, namely, that the amounts of response as well as the amounts of

stimulus must be numerically comparable. Moreover, in the absence of sureness of principle in case of the other three, the empirical check of agreement in result with those that have the needed sureness of principle has never been offered; yet sensitivities are determined just as if this condition did not exist, comparisons are made and conclusions are drawn. In short it may not be out of place to call attention here to the looseness of thinking and practice that prevails more or less generally with regard to the work of determining physiological sensitivities as compared with the analogous physical determinations. For the sake of consistency it might well be urged either that this work be revised on the basis of the standards set for the physical instruments with all of the interchecking of methods that is needed, or that the term sensitivity with its definite quantitative connotation be abandoned in all cases in which this standard can not be lived up to.

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I. INTRODUCTION

In a previous paper the purpose has been expressed of describing apparatus for work on the color sensitivity of the retina consisting of spectroscopic and radiometric features. In partial fulfillment of this purpose apparatus was described in a recent ıumber of the Journal of Experimental Psychology[1] designed to neet the following needs: (1) to stimulate any part of the retina vith the light of the spectrum and to control as desired the condiions of preexposure and surrounding field; and (2) to regulate he amounts of light used within the small gradations needed for hreshold and just noticeable difference determinations. It is the urpose of the present paper to describe apparatus with which it is ossible to specify the amount of light used in energy units. 'his completes the description of a group of apparatus by means f which it is possible to determine the sensitivity of the eye wave-length in terms that are commensurable, and thus to ace the investigation of the responses of the eye on a methodogical plane comparable with the study of the responses of the ıysical recording instruments. This could not be done until means was had of estimating light intensities which is not ıly independent of the achromatic and chromatic functioning of e eye itself, but which gives results directly proportional to the ysical value or energy of the light waves. An instrument ıich gives responses directly proportional to the intensity of the ht-waves is, we scarcely need to point out, equally sensitive to wave-lengths. With the responses of such an apparatus as ndard, the deviations of the eye from equal sensitivity to the ferent wave-lengths can readily be determined and compared.

Ferree and Rand. A Spectroscopic Apparatus for the Investigation of Color Sensitivity of the Retina, Central and Peripheral. J. of Experiıtal Psychology, 1916, *1*, pp. 247-283.

II. METHODS AND APPARATUS THAT HAVE BEEN USED FOR THE MEASUREMENT OF LIGHT INTENSITIES AND THEIR APPLICABILITY TO THE INVESTIGATION OF RETINAL SENSITIVITIES

No problem in optics probably has presented more difficulty t the investigator and the various committees which have bee appointed for the purpose by scientific and engineering societie bureaus, etc., than that of standardizing the intensity of light differing in color value. In the investigation of retinal sensitivi ties the problem of standardizing presents two aspects. (1) A the prime requisite of scientific work a method of specification i needed that will make possible an accurate and convenient repro duction of light intensities. Without this no investigation ca have the certitude that comes from repetition and verificatio And (2) an important item in the determination of retinal sens tivities has been a comparison of the sensitivity to different wav lengths. This has been made a feature of the general proble for the sake both of knowing the characteristics of the eye as sense-organ and measuring instrument, and of being able to me the many practical needs that have arisen in the attempt mo effectively to adapt light to the service of the eye in the work c lighting, etc. As we have already pointed out, if the sensitivit or responsiveness of the eye to lights of different wave-lengths to be compared, it is obvious that a common unit must be ha independent of the functioning of the eye itself, in terms of whi to measure the quantity or intensity of the light employed; or t express the need in another form, the light to be used in the i vestigation should be rated by instruments whose responses a directly proportional to the energy value of the light wave Such instruments being non-selective in their response to wav

[1] For a further statement of the conditions that must be fulfilled if t sensitivity of the retina is to be measured in a way that is comparable wi the measurement of the sensitivity of the physical recording instruments, s Preface, p. xi.

ngth and giving the true physical value of the stimulus are the gical standard of reference in the comparative study of instruents or organisms whose responses are selective. Fortunately struments for measuring light intensities which fulfill the above quirements have within the last few years reached such a stage advancement as to make this kind of treatment of the probm not only possible but feasible and even convenient. On this count a brief history may not be out of place here of the atmpts that have been made to attain measurements of light tensities which are purely physical.

Light of any wave-length is universally conceded to be a form motion in a transmitting medium. By common agreement iong physicists quantitative estimates of motion are made in ms of what is called energy of motion; or of mass and rate of tion. Owing to the small quantities of energy involved in the ves of the visible spectrum, it is obvious that light energies can t be estimated directly in terms of mass and rate of motion. me instrument or apparatus which responds to light must be d and the response of this instrument be calibrated against a rce of energy the radiation from which per unit of surface unit of time is known. Once calibrated, such an instrument h proper checks on its sensitivity may be used for the measurent of the visible radiations from any source. The requisites a satisfactory instrument for the physical measurement of t are obviously as follows. (1) It must give a response which irectly proportional to the energy of the light wave or must apable of calibration against an instrument which does give responses. (2) It should be non-selective in its response to e-length and to intensity, *i.e.*, it should be no more sensitive ne wave-length of the spectrum than to another and its sensiy should not vary with the intensity of the light used. This irement is an obvious corollary to the preceding. If an innent is used which is selective in its response to wave-length, imount of its selectiveness must be a constant else correction rs cannot be determined which will be valid for all intensi- (3) It should be sufficiently sensitive to respond to the small ints of light present in the visible spectrum. And (4) it

should give results which have a satisfactory degree of reproduc bility, or if erratic within known limits or conditions it must b calibrated against some instrument which does give reproducib results, and correction factors be determined.

As comparators of light intensities the following instrumen and the human eye have at various times been employed or in vestigated,—the Nichol's radiometer, the radio-micrometer, th micro-radiometer, the bolometer, the thermopile, the seleniu cell, the various types of photo-electric cell, and the photograph plate.[2] The following comparisons may be made of these instr ments with regard to the above mentioned requirements. (a The radiometer, the radio-micrometer, the micro-radiometer, t bolometer, and the thermopile, depending initially for their acti on heating effects, give responses which are directly proportion to the energy of the incident light. They are, therefore, no selective in their reaction both to wave-length and to intensit[3] The selenium cell, the photo-electric cell, the photographic pla and the human eye, however, do not give responses which a proportional to the energy of the incident light. They are l known to be selective in their reaction to wave-length; and the amount of this selectiveness in case of the selenium cell, e photographic plate and the human eye has been found to chare with the intensity of light. (b) All the instruments which e selective in their responses to wave-length, namely, the hum eye, the selenium cell, the photo-electric cell and the photograp c plate, have a high degree of sensitivity to light. The photograp c plate possesses the additional advantage that the action may e integrated over an interval of time. The instruments which e non-selective to wave-length are as a class less sensitive to lig t. Recent improvements in the construction of such instrume s,

[2] The use of these instruments for the measurement of light is base on the following effects produced by incident light: (1) heating effects; (a change in the resistance of certain metals to the flow of a current; (a decrease in the power of certain metals to hold a negative charge a partial vacuum; (4) chemical action; and (5) visual sensation,—used ch ly in connection with the various types of photometer.

[3] It should be mentioned, however, that their windows absorb select ly some of the wave-lengths of the invisible spectrum.

ıowever, have increased their sensitivity greatly. Of this class ›f instruments, the thermopile because of its greater ease of conrol and greater reliability is probably best adapted for use in ıboratories of physiological and psychological optics. Moreover, s was stated in our introduction, it has been developed to a high egree of sensitivity. In fact a comparative study of the nonelective instruments has shown that in the present stage of deelopment of such instruments, the thermopile possesses as high sensitivity as the others when operated in air and probably also hen operated in a vacuum. (c) The factors which influence ıe response and use of the instruments which are selective in ıeir action to wave-length have proven to be so hard to control ıat the results obtained have shown a comparatively low degree reproducibility. Of the non-selective instruments the boloeter is perhaps the hardest to control. The factors which inıence the action of the thermopile, the radiometer, and the dio-micrometer are on the other hand comparatively easy to ntrol. A comparative statement of the advantages and disadntages of these instruments will be given later in the paper.

Before considering these instruments in greater detail, it may of service perhaps to give a brief statement of the type of tion that is produced in each by the radiant energy falling upon receiving surface. As was stated earlier in the discussion, the ıasurement of energy by the types of instrument that are menned here is not direct. The instrument is available because it es to a greater or lesser degree some regular and constant type response to radiant energy, the value of which in energy units determined by calibration against the known radiations from a ck body, or from some other source whose radiations have been ermined by comparison with that from a black body. In ıtruments of the type of the radiometer, micro-radiometer, lio-micrometer, bolometer and thermopile, all radiations are ınsformed into heat at the receiving surface of the instrument. case of the radiometer, for example, the absorbed energy proes thermodynamic effects in the rarified gas contained in the ısing of the instrument, which in turn causes regular deflecıs of a delicately suspended vane; in case of the radio-microm-

eter and the thermopile, the absorbed energy acting upon a thermo-electric couple causes a flow of current which deflects the needle of a sensitive galvanometer in circuit with it; and in case of the micro-radiometer and bolometer, the absorbed energy changes the resistance to the flow of current in a delicately balanced electric circuit which is also detected by means of a sensitive galvanometer. The action of the remaining instruments is not due to heating effects; also these instruments are not responsive to all radiations. The selenium cell and the eye, for example are sensitive only to the visible spectrum (Brown and Sieg, however, Phys. Rev., 1914, *4*, (2), pp. 48-61, report one cell that has considerable sensitivity as far out as .85μ.) the photographi plate, when properly sensitized to red, and the photo-electric cel are sensitive both to the visible and the ultra-violet radiations.

In case of the selenium cell the visible radiations falling on a strip of metallic selenium placed in one arm of a delicately balanced electric circuit so change the resistance of the seleniun to the flow of current that the electromotive balance between th two arms of the circuit is disturbed, and a flow of current take place between two given points which were before at equal poten tials. This current deflects a galvanometer. The use of th selenium cell is attended with a great deal of difficulty and ther are many opportunities for cumulative error. The following is a brief statement of some of these difficulties. A detailed statemen will be given later in the paper. (1) As an instrument to b used in the process of measuring, it can be employed without cali bration (*e.g.*, the determination of sensitivity curves for differ ent intensities of light expressing a relation between respons and energy) only to identify equal amounts of energy; and sinc it is as a general case responsive only to light waves it can b used to equalize only light energies. Its employment in this way as a measuring instrument for the visible spectrum energies pre supposes, therefore, a standard light source, the energy values o the visible spectrum from which are known, against which t balance the unknown lights. But as stated earlier in the paper the light energy emitted from sources ordinarily available ca not be determined directly. It must be determined by compari

son with the radiations from some body the amount of which can be directly estimated. This comparison may be most conveniently made by means of some measuring instrument such as the thermopile which is responsive to the total of radiation and which is non-selective in its response to wave-length, and a black body radiating known amounts of energy to furnish the standard for the comparison. In short, without the possibility of ultimate recourse to such instruments as the thermopile, the radio-micrometer, etc., which are non-selective in their response to wave-ength, instruments of the class of the selenium cell would be ractically useless for radiometric purposes. Moreover, the two-old nature of the measuring operation, the difficulty of main-aining constancy of conditions in the employment of the sec-ndary standard, and more especially the many factors extrane-us to light which influence its response, make its use very liable o error. And (2) since the selenium cell is selective in its re-ponsiveness to the different wave-lengths of light, the standard ight source must in every case be of the same spectro-radiometric omposition as the light against which it is to be balanced, other-ise the cell can not be relied upon to give to the unknown light fair radiometric evaluation. That is, if the light to be meas-red is not of the same wave-length or composition as the stan-ard light, correction factors have to be used which represent e amount of the selectiveness of action. Furthermore, the mount of selectiveness of the action changes with the intensity f light, therefore correction factors established for one intensity ill not serve for all intensities.

The action of the photo-electric cell depends on the power of ght to cause certain metals to lose a negative charge of electricity a partial vacuum. Much that has just been said of the selenium ll applies also to the photo-electric cell. (1) It is not sensitive the infra-red spectrum, hence can not be calibrated directly gainst the total of radiation of a black body. (2) It is selective its response to the different wave-lengths of the visible spec-um. Griffith and Dember claim that it is also selective to in-nsity. (3) Its use in measuring the energy of the visible spec-um presupposes, for example, either some calibration similar

to that noted above for the selenium cell, or the availability of a light source the values of the visible radiations of which are known to serve as a standard against which to balance the unknown wave-lengths. And (4) its sensitivity is influenced by so many factors difficult of control as to give it a comparatively low reproducibility of response.

The photographic plate responds to light by a chemical change in its sensitive film, known as the 'blackening" of the plate. Its convenient use as an energy measuring instrument depends upon whether or not this blackening sustains any constant relation to the amount of incident light. If not, its use would necessitate such an elaborate calibration as to render it impracticable as a radiometer. Like the selenium and photo-electric cells, it too is selective both to wave-length and to intensity; its employment as an energy measuring instrument presupposes a standard light source, the energy value of the radiations from which is known; and its responses are subject to the influence of many variable factors which tend to give them a low degree of reproducibility.

The eye gives two responses to light waves, the chromatic and the achromatic. As yet the achromatic response alone has been used in the measurement of light intensities. Two possibilities are presented for the use of the eye as a measuring instrument: photometric or the rating of lights in terms of their power to arouse the achromatic sensation; and radiometric in the sense of balancing or equalizing the energy values of lights of the same spectro-radiometric composition. As an energy comparator the eye is like the selenium cell in the following regards. (1) It is responsive only to the visible spectrum. Its employment, therefore, presupposes the provision of a light source, the energy value of the visible radiations from which are known. And (2) since it is selective in its response to wave-length, it can without correction factors be used to establish an energy balance only between lights having the same spectro-radiometric composition. While not generally used or classed as radiometric, the eye can like the selenium and photo-electric cells be used very sensitively to balance energies of lights of the same spectro-radiometric

composition and has in this respect a similar claim to be considered as one of the radiometric possibilities. In fact our control of the factors which influence the response of the eye is perhaps enough greater than that of the selenium cell, the photo-electric cell, etc., to render its use for this purpose preferable from the standpoint of precision.

A. The Thermopile.[4]

The thermopile is probably the most celebrated of the radiometric instruments. To it we are indebted for the researches of Melloni and Tyndall as well as for the most notable advances that have been made in the study of radiation. The instrument was invented by Nobili and is based on a discovery made by Seebeck about 1820 that when two wires of different metals are joined end to end so as to form a closed circuit, an electric current passes around the circuit when one of the junctions is heated or cooled, and this current continues to flow as long as any difference of temperature exists between the two junctions.[5]

[4] With regard to the non-selective radiometers we are indebted heavily to the publications of Dr. Coblentz for data and for guidance in the compilation of data.

[5] There are three thermo-electric effects in metals: the Seebeck effect, the Peltier effect, and the Thomson effect. The Seebeck effect is described above and is the one on which the action of the thermopile is based. The Peltier effect discovered in 1834 is the converse of the Seebeck effect, *i.e.,* when a current is passed through a junction of dissimilar metals, the junction is either heated or cooled depending upon the direction of the current with reference to the thermo-electric relation of the metals. For example, if the current passes from the electro-negative to the electro-positive, work is done and the temperature of the junction is raised; but if it passes from the electro-positive to the electro-negative, the temperature of the junction is lowered. The result of the Peltier effect in a thermo-couple, therefore, is to lower the temperature of the exposed junction. This effect, however, is not considered to be sufficient to make an appreciable change in the results gotten with a thermopile-galvanometer combination of the sensitivity ordinarily obtained. The Thomson effect is a heat effect manifested when a current flows between points at different temperatures in the same metal. This effect differs in different metals. For example, when a current flows from a hot to a cold point in copper, it evolves heat; but when it flows from a cold to a hot point, heat is absorbed. In iron, however, the reverse is true. When the current flows from a hot to a cold point, heat is absorbed. This effect for the small temperature differences involved is also considered negligible by Altenkirch (Phys. Zeit., 1909, *10,* p. 560) in his discussion of the efficiency of thermopiles.

Like the bolometer the thermopile owes its effective sensitivity in part to its own construction and in part to the auxiliary galvanometer.

1. *Important points in the construction of sensitive thermopiles.* The problem in thermopile construction appears to be to secure a low resistance, a low heat capacity and heat conductivity, and a high thermo-electric power. The following have been found to be important points in the construction of thermopiles. a. *The metals used to form the thermo-electric junctions.* This point is of importance because metals are found to differ in their thermoelectric power, *i.e.,* in their electromotive force per degree centigrade when compared with the standard metal, lead. The following are some of the thermo-electric metals: bismuth, silver, German silver, lead, platinum, copper, zinc, iron, antimony, constantan, tellurium, and selenium. A very small amount of impurity may make a great difference in the thermo-electric power of a metal, and some of the alloys and metallic sulphides show a very high thermo-electric power. Some of the combinations most commonly used in making thermo-couples are bismuth and antimony, iron and constantan, and bismuth and silver. The bismuth and silver couple has been chosen by Coblentz because of its high thermo-electric power and low resistance. Silver was selected to complete the element with bismuth more especially because of its low resistance, its pliability and the ease with which it can be cleaned[6] and annealed. The latter two points are of great importance in the construction of the pile. Nicety of construction is of fact of greater importance to a high radiation sensitivity, Coblentz declares, than a high thermal E. M. F.[7] provided the material has a correspondingly high resistance.

[6] It is important that the metal chosen be easily cleaned for completeness of contact in soldering. A preliminary heating can be given the silver wire which serves the double purpose of cleaning and annealing. This preliminary heating could not, for example, be given to copper and iron wire.

[7] Coblentz (Bulletin of Bureau of Standards, 1914, 11, pp. 148-150) found, for example, in eight samples of bismuth wire with diameters of 0.06, 0.08, 0.1 and 0.15 mm. that the thermo-electric power when coupled with silver varied from 75 to 82 microvolts per degree, depending upon the purity of the material. Haken (Verh. Phys. Gesell., 1910, 12, p. 229) and Gelhoff and

b. *The size of the wire used in forming the couples.* The chief defects in the older types of thermopiles were their great heat capacity and their consequent lag in reaching a temperature equilibrium. The larger the wire used in making the couple, the greater, of course, will be the heat capacity. In the recent attempts that have been made to improve the linear thermopile a prominent item of change has been the use of finer wires, which not only decreases the heat capacity and lag and increases the radiation sensitivity, but permits more elements to be placed in a given area. The decrease in the size of the wire, however, increases the internal resistance which must of course be taken into account in planning for sensitivity. For example, Coblentz[8] found in experiments with surface thermopiles that a bismuth wire 0.15 mm. in diameter had sufficient heat capacity to require a half minute to attain thermal equilibrium, while a wire 0.1 mm. in diameter gave satisfactory results. Using this wire in conjunction with one of silver 0.0513 mm. in diameter as a standard of sensitivity, a silver wire of 0.041 mm. in diameter gave a sensitivity of 1.13; one of 0.03 mm. in diameter, a sensitivity of 1.20; and one of 0.021 mm. diameter, a sensitivity of only 1.12. That is, when the wire has reached an optimum fineness, any further decrease in size so increases the internal resistance as to more than

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Neumeier (*ibid.*, 1913, 15, p. 876) found that an alloy of bismuth with 9 to 0 per cent antimony gives a thermo-electric power which varies from 77 to 7 microvolts. Coblentz (*Op. cit.*, p. 149) found that an alloy of 5 to 6 per cent of tin gives a thermal E. M. F. of —44 to —45 microvolts per degree; and a thermo-element made of high grade bismuth and this alloy gives a thermo-electric power of 125 to 127 microvolts per degree.

While having 50 to 60 per cent higher thermo-electric power than a bismuth-silver pile, piles made of the bismuth alloy showed only about 10 per cent higher radiation sensitivity. The alloy is so much harder to handle that the same nicety of construction is not possible, also as high a durability is not attained. Since in making the silver-bismuth couple a bead of tin is used in soldering the two wires together, an alloy of bismuth and tin is made at the junction.

A bismuth-iron thermo-element (*op. cit.*, pp. 151-154) was found to give thermal E. M. F. which was 18 per cent higher than was obtained from bismuth and silver. No increase of radiation sensitivity was obtained, however, because the initial resistance was almost doubled by the use of the iron.

[8] Coblentz, W. W. Bulletin Bureau of Standards, 1913, 9, pp. 21-22.

compensate for the advantage gained by the lessened heat capacity. Johansen further says[9] that the radii of the two wires of the thermo-element should be so chosen that the ratio between the heat conductivity and the electrical resistance is the same in both.

c. *The dimensions of the pile and the number and arrangement of the receiving thermo-couples.* In a recent theoretical contribution to the construction of thermopiles for the measurement of radiant energy, more especially the construction of vacuum thermopiles, Johansen[10] arrives at the conclusion that the radiation sensitivity is proportional to the square root of the exposed surface in case of the thermopile as it is in case of the bolometer. In extensive experimental determinations of the point, however, Coblentz[11] finds (a) that in single thermo-couples the sensitivity is not proportional to the square root of the area exposed to radiation, but that the area has an optimum value which gives a considerably higher sensitivity than is required compatible with the square root law; and (b) that the highest sensitivity is attained by building up a composite receiver of elements having individual receivers of a size giving the maximum sensitivity.[12] It is obvious, therefore, that sensitivity can be added to the instrument by increasing the total area of the receiving surface and consequently the number of thermo-couples, the individual receivers of which make up the total area; and that the maximum increase can be attained by having each individual receiver of the optimum size. In one of his more recent models of linear thermopiles

[9] Johansen, E. S. Ann. der Phys., 1910, 33, (4), p. 517.

[10] Johansen, E. S. *Loc. cit.*

[11] Coblentz, W. W. Bulletin of Bureau of Standards, 1914, *11*, p. 142.

[12] From the data obtained in constructing the receiving surface in this way, he concludes that the gain in sensitivity over what is indicated by the square root law amounts probably to as much as 50 per cent.

According to Coblentz the requisite of the optimum size is that it shall absorb radiant energy at a rate which will just compensate for the loss of heat from conduction along the wires. If this size is exceeded, the loss from emission becomes even greater than the loss by conduction along the wires and the two together operate to give less than the maximum difference of temperature attainable between the "hot" and "cold" junctions of the couple. A lag in reaching a thermal equilibrium also results because the heat is drained off from the center of the receiver faster than from the edges by conduction along the wire.

Coblentz[13] uses, for example, 22 junctions of bismuth and silver mounted in a space 10.5 mm. long. The width of this pile was 5 mm. and its resistance was 10.8 ohms.[14] In the surface thermopile greater sensitivity may of course be attained than in the linear. The surface pile is in effect built up of contiguous linear piles.

d. *The type of connection of the couples.* In the older types of thermopile it was the custom to connect the couples in series. Coblentz[15] has found, however, that it is of advantage to substitute a series-parallel connection. In the series connection one thermo-couple is attached to each of the overlapping receivers on the front of the pile, while in the series-parallel arrangement two couples are soldered to each receiver. The effect of this type of connection is in the first place to reduce the number of overlapping receivers by one-half. This reduces the superfluous metal at the lap and the amount of insulation required, and gives the apparatus a quicker response. And secondly the internal resistance is reduced to one-fourth what it would be if the elements were all connected in series; so that although their E. M. F. is reduced by one-half by the series-parallel arrangement, there is a gain of from 10 to 12 percent. in radiation sensitivity.

e. *The relation of internal to external resistance.* It has been a commonly accepted principle in the construction of thermopiles that the highest sensitivity is attained when the resistance in the thermopile is equal to the resistance of galvanometer and connecting wires. Rayleigh,[16] for example, in his computation of the thermodynamic efficiency of the thermopile has shown that the useful work done externally attains a maximum when the external resistance is equal to the internal resistance. In these computations only the specific resistances and the thermal conductivities were considered. Altenkirch,[17] 1909, however, contends that the

[13] Coblentz, W. W. Bulletin of Bureau of Standards, 1913, *9*, p. 292.

[14] The linear pile that has been used in the work that has been done in this laboratory is of this type with the exception that the receiving surface, designed for spectroscopic work, has a breadth of only 2 mm.

[15] Coblentz, W. W. Bulletin of the Bureau of Standards, 1914, *11*, pp. 138-142.

[16] Rayleigh. Phil. Mag., 1885, *20* (5), p. 361.

[17] Altenkirch, E. Phys. Zeit., 1909, *10*, p. 560.

external resistance may be two or three times the internal resistance without seriously affecting the maximum efficiency of the thermopile, and Coblentz,[18] 1914, finds that the external resistance may be two or three times the internal resistance without decreasing the sensitivity of the instrument more than 5 to 10 percent.

f. *Nicety of construction.* Coblentz makes the statement that the attainment of a high radiation sensitivity in a thermopile is at the present stage of development of thermopile making mainly a question of nicety of construction, for upon this more than any other point depends the low heat capacity, conductivity and emissivity needed for a sensitive instrument. The following are some of the points that should be taken into account in attaining the most effective relation between capacity, conductivity and emissivity,—the kind of materials, the size and form of the wires used for the couples, the length of wire, the size of the receiving surface, the type of connection of the couples, the relation of size of slit to size of receiving surface, the amount of insulation material, etc.[19] The object to be attained by a low heat capacity, conductivity and emissivity is of course that the energy falling on the receiving surface shall cause a maximum rise of temperature and that there shall be as little lag as is possible in the rise to

[18] Coblentz, W. W., *op. cit.*, p. 175.

[19] Coblentz attributes a great deal of his success in the construction of thermopiles to the use of his electrically heated welding device. (See Bull. Bureau of Standards, 1913, 9, p. 16); to the choice of silver wire which is easily cleaned and annealed; and to his use of pure tin in the process of welding which produces an alloy which is not brittle.

He cites cases to show the effect on sensitivity of deviations from the general method of construction. For example, the central line of receivers of one thermopile was given an additional coat of shellac to cause the individual receivers to adhere, instead of causing the adhesion by merely moistening the insulating layer with alcohol. The instrument was slow in responding to a radiation stimulus and was besides insensitive. This extra shellac was then removed by means of blotting paper wet with alcohol, and the surfaces resmoked. The radiation sensitivity was increased 40 to 50 per cent. In another case a thermopile was made of 0.1 mm. wire pressed flat. This thermopile had a radiation sensitivity 25 to 30 per cent less than the average sensitivity of a number of similar thermopiles made of round wire. The flat wire which presented a greater surface for radiation increased the emissivity and thus lowered the sensitivity of the instrument.

thermal equilibrium. When this is attained the instrument will respond quickly and give its maximum response.

g. *Provisions to secure steadiness of response.* The main source of unsteadiness of response is exposure to air currents. This of course can be completely eliminated by isolating the instrument from the air. The best success of isolation is evacuation which doubles the sensitivity. Water jackets and combinations of water and air jackets have been used also. Unlike the bolometer, however, the thermopile is noted for its steadiness of response in air. This is one of the strongest recommendations for its general use.

Older forms of thermopiles used by Melloni, Tyndall and others were subject to a "drift"; *i.e.*, there was a permanent E.M.F. which caused a permanent deflection of the galvanometer. This permanent E. M. F. seems at least in part to have been due to lack of symmetry in the construction of the "hot" and "cold" junctions. In our own linear thermopile this tendency to drift was overcome by soldering on the "cold" junctions receiving surfaces of tin of the same dimensions as were carried by the "hot" junctions.

2. *Advantages of the thermopile.* (1) It is non-selective in its response to wave-length. (2) It is readily portable and is easily adapted to the many needs for which a sensitive radiometer is needed. (3) In its most improved forms it is very steady in its action. Even when used in air there is comparatively little drift. (4) A high degree of sensitivity has been obtained. Coblentz[20] with a single thermo-couple in a vacuum and a 3-foot telescope has recently made quantitative measurements of the radiations of stars of the fifth magnitude and detectable responses were obtained from stars of the seventh magnitude. The instruments used by us are abundantly sensitive to measure the visible spectrum. (5) It is already attainable in forms adapted to special purposes. Coblentz[21] for example, describes thermopiles for the following purposes: for stellar

[20] Coblentz, W. W. Publications of the Astronomical Society of the Pacific, 1914, *26*, pp. 169-178.

[21] Coblentz, W. W. Bulletin of Bureau of Standards, 1914, *11*, p. 163.

measurements, and the measurements of other nocturnal radiations; for the measurements needed in physical photometry; for the determination of whether or not heat is generated in the tetanization of a nerve (an ingenious device in which the thermo-couple is made into a U-shaped trough for the reception of the nerve); and for various miscellaneous purposes which need not be gone into here. Its feasibility and wide range of utility are attested by the fact that it is now being used with success and a fair degree of convenience in radiation work in physical, chemical, biological and psychological laboratories. Owing to the recent improvements that have been made in its sensitivity, its quickness and steadiness of response, and the ease and convenience with which it can be operated, it seems to be the most promising of the radiation instruments now available, especially for the use of the experimenter who is not a radiometric specialist. These improvements mark, it is to be hoped, an epoch in the quantitative study of phenomena in the production of which radiation plays a part.

B. The Nichol's Radiometer

The radiometer was first described by Crookes[22] in 1874 as an interesting scientific toy. Some years later it was used in a somewhat modified form to investigate the infra-red spectrum to about 1.5μ.[23] The first really useful radiometer was developed by Nichols in 1896.[24] It was further developed and improved by Coblentz in 1905.[25] In its modern form the radiometer consists of two similar thin vanes of mica or platinum blackened on one side which are held together by glass fibres and are suspended in a vacuum by means of a fine quartz fiber. The vanes are about 3 mm. from an opening or window in the housing of the apparatus. The radiations to be measured fall upon one of the vanes which becomes slightly warmed. This

22 Crookes, W. Philos Trans. 1874, *164*, p. 501; 1875, *165*, p. 519; 1876, *166*, p. 325.

23 Pringsheim, E. Ann. der Phys. 1883, *18*, p. 32.

24 Nichols, E. F. Berichte der Berliner Akad., 1896, p. 1186; Phys. Rev., 1897, *4*, p. 297.

25 Coblentz, W. W. Investigations of Infra-red Spectra. Carnegie Publication, No. 35, Washington, 1905, p. 21.

auses the residual gas molecules to rebound with increased ve- ocity from the blackened surface and the reaction pushes this ane from the window causing a rotation about the axis of sus- ension. A small mirror is attached to the glass fiber which forms e axis of rotation, and the deflection is observed by means of a lescope and scale.

1. *Significant points with regard to the radiometer.* The havior of the radiometer has been worked out theoretically by axwell[26] in his paper on "Stresses in Rarefied Gases Arising om Inequalities of Temperature." Crookes, Nichols, and others ve shown that the sensitiveness of the radiometer is a function the pressure of the residual gas surrounding the vanes, of the nd of gas, and of the distance of the exposed vanes from the ndow. Investigation by Coblentz[27] has also brought out the lowing points. (1) For vanes of small dimensions such as ist be used in practical work, the deflections are found to be oportional to the area of the exposed surface of the vane.) The sensitiveness varies with the diameter of the suspension er. (3) The instrument is not selective in its response.

2. *Comparative advantages and disadvantages of the radio- ter.* As a working instrument the radiometer is said to have following advantages. (a) Its sensitiveness is comparatively y to control since it can be made to depend almost entirely n the pressure of the residual gas. (b) It is not uenced by magnetic and thermo-electric disturbances which der work with a very sensitive galvanometer tedious and un- sfactory. (c) It is not so sensitive to temperature changes s, for example, a bolometer, and it can be more easily shielded n changes in temperature than can a bolometer with its galva- neter, battery, etc. It has the following disadvantages. (a) not portable, which may cause inconvenience in certain types vork. (b) For maximum sensitiveness its period is very long ompared with that of a bolometer or thermopile and galva- eter combination. (Nichols used a period of 8-12 sec., single

Maxwell, J. C. The Scientific Papers of, *2*, p. 681; Philos. Trans., 1879, p. 231.

Coblentz, W. W. Bull. Bur. Standards, 1907, 4, p. 405.

swing; Coblentz 30-45 sec.) This makes the instrument slow to operate. As a compensating feature, however, as Coblentz points out, the readings are always trustworthy so that there is no need to repeat them. (c) Its window or preferably double window is selective in its transmission in the invisible parts of the spectrum. A correction has, therefore, to be applied to the results for this inequality when working in this region.

C. The Radio-micrometer.

This instrument was invented independently by d'Arsonval[28] and by Boys.[29] It combines in one instrument the thermo-couple which in response to the radiant energy generates the electric current, and the galvanometer which indicates by its deflections the comparative amounts of current. That is, the radio-micrometer is essentially a moving coil galvanometer, the moving coil of which contains one or more thermo-junctions. In the instrument devised by d'Arsonval a single loop of wire was used, one part of which was silver and the other palladium. In the instrument devised by Boys the moving coil consisted of a loop of copper wire to which was soldered a thermo-junction of bismuth and antimony. These instruments not having been found to possess the sensitivity attributed to them by their inventors, various attempts have been made to improve them but with little success. Paschen,[30] for example, tried to increase the sensitivity by increasing the number of thermo-junctions.[31] Different thermo-couples have been employed

28 d'Arsonval. Soc. Franc. de Phys., 1886, pp. 30, 77.

29 Boys, C. V. Proc. Roy. Soc. 1887, *42*, p. 189; 1888, *44*, p. 96; 1890, *47*, p. 480; Philos. Trans., 1889, *180A*, p. 159.

30 Paschen, F. Ann. der Phys., 1893, (3) *48*, p. 272.

31 An advantage is gained in the thermopile by increasing the number of thermo-couples, but not in the radio-micrometer. In a thermopile the highest efficiency is attained when the resistance of the thermo-couples is equal to the combined resistance of the connecting wires and the auxiliary galvanometer. Since the resistance of a single thermo-couple is much less than this combined resistance, it is of advantage to use several pairs of junctions. In the case of the radio-micrometer, however, the connecting loop of wire has a negligible resistance, hence there is nothing to gain by using more than a single pair of junctions; for as the electromotive force is increased by the addition of junctions, there is a proportionate increase of resistance and the throw of current remains constant.

'éry,[32] for example, used silver and constantan; Schmidt[33] bis-nuth and antimony; and Coblentz,[34] also bismuth and antimony, nd later bismuth and silver.[35] Hollnagel[36] added greatly to the ensitivity and constancy of the instrument described by Schmidt y operating it in a vacuum; Coblentz[37] increased the sensitivity of is bismuth-silver radio-micrometer by enclosing it in a vacuum; nd Rubens and Hollnagel,[38] and Rubens and Wood[39] succeeded ı obtaining an increase of sensitivity for the instrument de-ribed by Schmidt by using a concentrating or conical receiver. oblentz also found that the sensitivity of his instrument was wered by para- and dia-magnetic effects produced by the field agnets. He was able to lessen these effects and add thereby to e delicacy of response by using weak field magnets; or if strong, placing them as far above the thermo-junctions as was possible. ıe elimination of these effects he considers one of the chief stacles to be overcome in the future construction of the strument.[40]

As a working instrument the radio-micrometer may be said to ve the following advantages: (a) It is self-contained; (b) it is n-selective in its response to wave-length; (c) it is little subject magnetic perturbations; and (d) it has a high constancy of zero-reading.

Fery, C. Comptes Rendus, 1909, *148*, p. 915.

Schmidt, H. Inaug. Diss., Berlin, 1909; Ann. der Phys., 1909, *29* (5), 004. See also U. Meyer. Ann. der Phys., 1909, *30* (5), p. 612.

Coblentz, W. W. Bulletin Bureau of Standards, 1906, *2*, p. 479.

On p. 10 (Bulletin Bureau of Standards, 1913, *9*), Coblentz says: "From experience it seems desirable to try constantan instead of bismuth."

Hollnagel, H. Inaug. Diss., Berlin, 1910.

Coblentz, W. W. Bull. Bureau of Standards, 1906, *2*, p. 479; 1908, *4*, 16.

Rubens, H. and Hollnagel, H. Sitz Ber. d. königig. Preuss. Akad. Wiss., in, 1910, No. *2*, p. 26.

Rubens, H. and Wood, R. W. *Ibid.*, 1910, No. 52, p. 1122.

For further reports of work with the radio-micrometer see Lewis, . Astrophysical Journal, 1895, *2*, p. 1; Wilson, W. E. Proc. Roy. Soc., *55*, p. 246; 1895, *58*, p. 174; 1896, *60*, p. 377; and Julius, W. T. Hand-en, 5, de Nederlandisch Natuur en Geneeskundig Congress, 1895.

D. The Bolometer.

As has already been stated the bolometer is an instrument depending for its response to radiant energy on the change in resistance with change in temperature offered by a metal to the flow of an electric current. The instrument is essentially a Wheatstone bridge, two arms of which are made of very thin blackened metal strips (of high electrical resistance and high temperature coefficient), one or both of which are exposed to radiation. When thus exposed there is a change of temperature which unbalances the bridge, and the resulting deflection of the needle of the galvanometer in circuit with the bridge gives a measure of the energy absorbed. In order that the instrument shall be sensitive to small radiation quantities, it is obvious that the metal used should have a high temperature coefficient of resistance, a small specific heat, and a low heat conductivity. Such metals are nickel, platinum, tin, and iron. For various reasons relating to mechanical construction, however, platinum is much more frequently used than the others.

The earliest account of an instrument depending on change of electrical resistance for measuring or detecting radiant energy appears to be that of Svanberg, 1851,[41] who for this purpose introduced a flat spiral of blackened copper wire into one of the arms of a Wheatstone bridge. Langley, 1881,[42] was the first however, to invent a practical instrument and demonstrate its superiority to all radiation meters existing at that time for accuracy, quickness of action, and adaptability. As is shown in the reference appended below, his improvements of the instrument extended over a long period of time. The value of these improvements may be shown by comparing the sensitivity of his earlier and later instruments. The first had a sensitivity of 0.00002° per mm. deflection of the galvanometer, and the latest recorded a temperature change of 0.000001° per mm. deflection when used with a galvanometer having a figure of merit of $i = 5 \times 10^{-10}$ ampere.

[41] Svanberg, A. F. Pogg. Ann. der Phys., 1851, *84*, p. 416.

[42] Langley, S. P. Proc. Amer. Acad., 1881, *16*, p. 342; Chemical News 1881, *43*, p. 6; Brit. Assoc. Report, 1894, p. 465; Annals Astrophys., Obs. I

1. *Important points in the construction of sensitive bolom-*'*ters.* Obviously effective sensitivity can be added in two vays in the use of the bolometer: (1) by improving the bolom-'ter itself; and (2) by making more delicate the auxiliary ;alvanometer. In the attempt to construct sensitive bolometers vith as great constancy of the zero as is possible, the following re some of the points that have received attention.

a. *The kind of material to be used for the receiving surface.* .s has been stated the problem is to get a metal having a high :mperature coefficient of resistance, low specific heat; and low onductivity of heat.[43] The following metals have at various mes been used: platinum,[44] tin,[45] nickel,[46] and iron.[47]

b. *The area of the receiving surface.* The sensitiveness has en found to be closely proportional to the square root of this rface. In spectral energy work, therefore, where the bolometer rip is narrow the sensitiveness attainable for the bolometer is nited.

c. *The thickness of the strip used as receiver.* There is a :chanical limit to the thinness of the strip that can be used when posed to the air. Langley[48] found that platinum strips, for

[3] According to Lummer and Kurlbaum (Wied. Ann. der Phys., 1892, *46*, :08) the following equation expresses the relation between the sensitive-s of the bolometer, S; the bolometer current, I; the temperature coefficient :he area exposed to radiation, e; the area of the strip exposed to radia-, a; the resistance of the bolometer strips, r; the absorption coefficient he surface exposed to radiation, A; the emissivity of the whole surface, the area of the whole surface, F; the heat capacity, W; and the galva-eter constant, k.

$$S = \frac{I}{8}\,eak\sqrt{r\,\frac{f_1(A)\,f_3(F)}{f_2(E)\,f_4(W)}}$$

n this equation it will be seen that the sensitiveness is increased by easing the heat capacity and the emissivity; and by increasing the neter current, the temperature coefficient, the resistance, the absorp-coefficient, and the surface.

[4] Langley, S. P. *Loc. cit.*

[4] Ångström, K. Wied. Ann. der Phys., 1885, *26*, p. 253; 1889, *36*, p. 715; *68*, p. 493, and others.

[4] Julius, W. T. Licht und Wärmestrahlung, 1890, p. 31.

[4] Rubens, H., (used tin, iron, and platinum). Wied. Ann. der Phys., 8 *37*, p. 255; and 1892, *45*, p. 238.

[4] Langley, S. P. *Op. cit.*

example, less than 0.002 mm. thick are inadvisable, thinner ones being disturbed mechanically by air currents. In recent work Coblentz[49] finds it permissible to use platinum strips 0.001 mm. in thickness. In vacuum bolometers, however, much thinner strips (0.0005 mm.) are used to advantage.

d. *The most favorable resistance of bolometer and balancing coils.* Lummer and Kurlbaum[50] considered the bolometer a simple Wheatstone bridge which has its maximum sensitiveness when the four arms and the galvanometer are all of equal resistance. In fact in the construction of their instrument instead of using one or two bolometer surfaces, they used four just alike each forming one of the arms of the bridge.[51] Child and Stewart,[52] however, have shown experimentally that the sensitiveness is increased by having the resistance of the balancing coils several times that of the bolometer strips. Abbot[53] has also shown that the maximum sensibility is very nearly attained when the resistance of the balancing coils is four times or more that of the bolometer strips, and the galvanometer resistance is not less than 0.6 or more than four times the resistance of the bolometer strips.[54]

e. *The slide wire for balancing the resistance.* The question of a satisfactory slide wire has required considerable attention. Coblentz has found that slide wires of platinum 0.5 and 1 mm. in diameter used in connection with a mercury contact give the best satisfaction.

f. *The protection of the bolometer from air currents.* This can be done adequately only by putting the bolometer in vacuum. Contact with the air renders the bolometer both insensitive and inconstant in its response. On the former point

49 Coblentz, W. W. Bulletin of the Bureau of Standards, 1912, *9*, p. 37.

50 Lummer, O. and Kurlbaum, F. Wied. Ann. der Phys., 1892, *46*, p. 204.

51 The tendency among foreign investigators has been to make the four arms of equal resistance. On the other hand just as strong a tendency has been shown among American investigators to make the resistance of the balancing coils greater than that of the bolometer strips.

52 Child, C., and Stewart, O. Phys. Rev., 1897, *4*, p. 502.

53 Abbot, C. G. Annals of the Astrophysics Obs., I.

54 See also Reid, H. F. Amer. Jour. Sci., 1888, *33*, (3), p. 160.

Varburg, Leithäuser, and Johansen[55] have shown that the heat ost by air conduction for a bolometer 1 mm. wide is 4.5, and for . bolometer 0.2 mm. wide, 14.8 times as great as it is from adiation. And in a vacuum a bolometer 0.2 mm. wide when perated with a small current was found to be ten times as sensi-ve as it was in air.[56]

g. *The strength of current.* The radiation sensitivity of a acuum bolometer is found to be proportional to the current for nall values but for a large current the radiation sensitivity of a arrow bolometer passes through a maximum. This maximum is otained for a current density at which the radiation sensitivity of e air bolometer does not depart appreciably from proportionality ith the current. The manner in which the radiation sensitivity aries with the gas pressure and with the bolometer current is own, for example, by Buchwald.[57]

2. *Points in the construction of the auxiliary galvanometer.* is scarcely necessary to mention that the effective sensitivity of e bolometer depends in a large measure upon the auxiliary lvanometer. The first great step in improving the moving agnet galvanometer is due to Kelvin who decreased the weight the moving parts to a few milligrams, and introduced the static stem of magnets. Snow[58] was among the first to give much at-tion to the possibility of adding sensitivity to the bolometer by proving the galvanometer. Paschen[59] continued the work in s direction and constructed the most sensitive galvanometer d up to that time. DuBois and Rubens,[60] Mendenhall and

Warburg, E., Leithäuser, G. and Johansen, E. Ann. der Phys., 1907, (5), p. 25.

A noteworthy vacuum spectro-bolometer is described by A. Trowbridge ys. Rev., 1908, *27*, p. 282; Philos. Mag., 1910, (6), *20*, p. 768) in which bolometer and the optical parts of the spectroscope are in a vacuum. entz also describes a very sensitive vacuum bolometer and gives results it at different pressures (Bull. Bureau of Standards, 1913, *9*, pp. 39-43). r less adequate methods of shielding have been to surround the bolom- by a double wall with an air space between; to enclose it in a water et (Langley, *op. cit.* and Abbot, *op. cit.*); etc.

Buchwald, E. Ann. der Phys., 1910, (4), *35*, p. 928.

Snow, B. W. Phys. Rev., 1895, *1*, p. 31.

Paschen, F. Wied. Ann. der Phys., 1893, *48*, p. 272.

DuBois and Rubens. Ann. d. Phys., 1900, (4), *2*, p. 84.

Waidner,[61] Abbot,[62] Ingersoll,[63] and Coblentz[64] have all described sensitive galvanometers. Some of the points to be considered in the construction of a sensitive galvanometer are form and size of coil, size of wire, the kind of magnet and the dimensions and construction of the needle system, the astaticizing of the magnet system, the shielding of the system from influences due to the earth's field and neighboring objects, etc. The proper form and method of winding galvanometer coils to secure a maximum effect from a given weight or resistance of copper has been thoroughly discussed by Maxwell.[65] He shows that the greatest effect is obtained by winding the coils with different sizes of wire, beginning with the smallest size and winding each layer so that it lies within the surface the polar equation of which is $r^2 = d^2 \sin \theta$, where r is the length of the radius making an angle θ with the axis of the coil, and d the value of r when $\theta = 90°$. Abbot[66] has computed the most efficient coils for meeting these conditions, and gives results for coils wound with a single wire and for coils wound with three sections of wire of different diameters. He found that the total force exerted at the center is closely proportional to the 0.45 power of the total resistance and that coils composed of three sections of the best sizes of wire give 1.4 times the force of a coil of the best single size wire of the same total resistance. In his best 25 ohm coil, wound in three sections the diameters of the wires were 0.08, 0.16, and 0.32 mm.; the lengths were 256, 1031, and 4144 cm.; and the external diameter of the completed coil was 3.3 cm.

In the construction of the needle system the greatest sensitivity is attained when the ratio of the magnetic moment to the moment of inertia of the system is a maximum. The best dimensions and construction of needle systems have been extensively investigated

61 Mendenhall, C. E. and Waidner, C. W. Amer. Journ. Sci., 1901, 12, (4), p. 249.

62 Abbot, C. G. Astrophys. Journ., 1903, *18*, p. 1.

63 Ingersoll, L. R. Philos. Mag., 1906, (6), *11*, p. 41.

64 Coblentz, W. W. Bulletin Bureau of Standards, 1908, (3), *4*, pp. 424-435; 1916, *13*, p. 423.

65 Maxwell, J. C. Electricity and Magnetism, *2*, p. 322.

66 Abbot, C. G. *Loc. cit.*

by Paschen, Mendenhall and Waidner, and by Abbot. The shielding of the galvanometer from magnetic perturbations, etc., is done by means of housings of soft iron. For an inexpensive and convenient method of shielding, for a simplification of the moving coil galvanometer for convenience of shielding, and for the astaticization of the needle system, see Coblentz (*loc. cit.*).

3. *Possible sources of difficulty in the use of the bolometer.* The preceding discussion though brief may be enough to indicate that the bolometer is a difficult instrument to operate. The following are the possible sources of trouble. (1) The auxiliary galvanometer is subject to magnetic perturbations and if exposed to great temperature changes its sentiveness is changed, due to a variation in the resistance of the coils. The sensitiveness and zero reading are also subject to frequent changes due to variations in the magnetic field. (2) The bolometer strip is affected by air drafts, and, if very thin, by mechanical vibration. (3) The electric circuits are subject to temperature (resistance) changes which cause variations in the bolometer current. (4) The storage battery current is irregular due to changes in temperature and to polarization. (5) The gases surrounding the bolometer may affect the readings. Lummer and Pringsheim[67] found, for example, that variations in the amount of moisture in the air change the sensitiveness of the bolometer. A part or all of these causes tend to make the readings in work with the bolometer extremely variable. These variations are of two kinds. (a) A slow drift of the zero scale reading due to changes in the resistance of the bridge; and (b) fluctuations of the reading due to air currents and magnetic perturbations.

4. *The comparative advantages and disadvantages of the bolometer.* The bolometer has, however, the following advantages. It has a high degree of sensitivity. It is portable. It is non-selective in its response to wave-length. It can be calibrated directly against a black body. It is quick in its action and is, therefore, well adapted to work in which a quick registration of the galvanometer deflections is desired. Its chief disadvan-

[67] Lummer, O. and Pringsheim, E. Ann. der Phys., 1897, (3), *63*, p. 398.

tage, as has been stated, is its unsteadiness and the difficulty of operating. It is not nearly so easy to operate as the thermopile, for example; and the unsteadiness of its zero point renders it untrustworthy for small readings in spite of its high intrinsic sensitivity.

E. The Selenium Cell

To Willoughby Smith belongs the discovery that has led to the use of selenium as a light-measuring instrument. In 1873 while using a resistance made of selenium in connection with experiments in telegraphy, he discovered that its electrical conductivity is raised by exposure to light. The immediate result of this discovery was twofold: light-measuring instruments were constructed of selenium, and a long series of investigations was begun to determine (a) the factors extraneous to light that influence the resistance of selenium and thus affect its applicability to the measurement of light; (b) the factors that influence the action of light on the conductivity of a selenium cell and the possibility of the use of the cell either as a photometer or a radiometer; and (c) the nature of the action of light on the specific resistance of selenium.

A selenium cell is a device consisting essentially of a mass of crystalline selenium furnished with two metallic electrodes. Crystalline selenium is obtained by keeping molten vitreous selenium at a temperature of from 150 to 210° C. for several hours. It then takes on a metallic appearance and becomes opaque even in case of very thin films. Selenium has such a very small conductivity that in making resistances of it, one feature of the construction is to offer several paths or rather one continuous broad path for the flow of current. One way in which this has been accomplished in the construction of light-measuring cells has been to wind a strip of mica or slate with two parallel wires less than 1 mm. apart. This is covered with powdered selenium. The selenium is melted, worked into a smooth surface and cooled quickly. It is then heated again and cooled very slowly. One end of each wire is connected to the battery terminals, the others end in the selenium. The wires thus in reality form the electrodes, and the circuit is completed through the intervening selenium. This type

of cell has been used among others by Bidwell, Siemans, Sabine, and Pfund. (For construction of selenium cells, see Bidwell,[68] Fritts,[69] Berndt,[70] Townsend[71] and Dieterich.[72])

1. *Points to be considered in the construction and use of selenium cells.* The following are some of the points to be considered in the construction and use of sensitive selenium cells.

a. *The method of preparation.* The sensitiveness of the cell to light depends largely upon its initial specific resistance. This has been pointed out by Pochettino[73], Giltay,[74] and especially by Brown.[75] According to Brown, the higher the resistance of crystalline selenium the greater is its sensitivity to light; and conversely the lower its resistance, the less is the sensitivity. Brown gives results showing the resistance of the cell and its sensitivity in terms of the ratio of conductivity in light to conductivity in the dark. For example, a cell with a resistance of 10^9 ohms had a sensitivity of 200:1 in an arbitrary scale; a cell with a resistance of 400,000 ohms, a sensitivity of 30:1; 3,000 ohms, 2:1; 1,700 ohms, 1:1. In its vitreous state selenium is practically a non-conductor. To become a conductor it must be brought to the crystalline form. For example, when it is heated to a temperature of 100 to 150° C. its conductivity is slight and variable; but when heated repeatedly to temperatures of 190 to 210° C. and cooled, it passes into a coarsely granular crystalline state and acquires and retains a greater conductivity. That the temperature to which selenium has been heated is the chief factor in determining its conductivity and sensitivity to light was pointed out by Siemans[76] as early as 1875, who stated that when heated to 210° C. cells of greater conductivity, constancy, and light sensitivity were produced than when heated to 150° C. A systematic study of the

[68] Bidwell, S. Phil. Mag., 1891, Ser. 5, *31*, pp. 250-256; 1895, *40*, pp. 233-256.
[69] Fritts. Electrical Review, 1885, p. 208.
[70] Berndt, G. Phys. Zeit., 1904, *5*, pp. 121-124.
[71] Townsend, F. Electrician, Oct. 7, 1904, *53*, pp. 987-990.
[72] Dieterich, E. O. Phys. Rev., 1914, *4*, Ser. 2, pp. 467-476.
[73] Pochettino, A. N. Cimento, 1911, *1*, Ser. 6, pp. 147-210.
[74] Giltay, J. W. Phys. Zeit., 1910, *11*, p. 419.
[75] Brown, F. C. Phys. Rev., 1911, *33*, pp. 1-26.
[76] Siemans, W. Phil. Mag., 1875, *50*, p. 416.

effect of temperature and the duration of annealing on the resistance of selenium has been made by Dieterich.[77] His results show that when maintained at a temperature of 200 to 210° C. for six hours, a cell was produced with a resistance of 233,000 ohms; at 210° for four hours, a resistance of 358,000 ohms; at 210° for five hours, 490,000 ohms; at 180° for three and one-half hours, 1,400,000 ohms; and at 190° for two hours, 3,690,000 ohms. Inasmuch as his cells of highest resistance were not permanent, he was not able unfortunately to work out the correlation between resistance and sensitivity. Pochettino,[78] Aichi and Tanakadate,[79] Brown,[80] and Dieterich[81] all think that a change of structure takes place when selenium is annealed at a temperature of 210 to 220° which causes the increase of conductivity.

b. *Purity of the selenium.* Bidwell[82] found that insensitive selenium cells were increased in sensitivity by the addition of a small quantity of cuprous selenide. Marc[83] recommends the addition of 0.1-0.5% of silver to increase its sensitivity. Townsend[84] claims that 1 or 2% of copper or nickel selenide may be present without affecting to a marked degree the sensitivity of the cell. Pfund[85] found that the sensitivity could be increased by the presence of 3% of a selenide. He believes it to be of advantage, however, to start with a chemically pure selenium and add impurity of a definite kind and amount.

c. *Material and size of electrodes.* Sale,[86] and Adams and Day[87] used platinum electrodes; Bell[88] used brass; Bidwell,[89]

[77] Dieterich, E. O. *Loc. cit.*

[78] Pochettino, A. N. Cimento, 1911, *1*, Ser. 6, pp. 147-210.

[79] Aichi, K. and Tanakadate, T. Math. and Phys. Soc., Tokyo, 1904, (2), *16*, pp. 217-221.

[80] Brown, F. C. *Loc. cit.*

[81] Dieterich, E. *Loc. cit.*

[82] Bidwell, S. Phil. Mag., 1895, *40*, Ser. 5, pp. 233-256.

[83] Marc, R. Z. Anorg. Chem., 1906, *48*, pp. 393-426.

[84] Townsend, F. *Loc. cit.*

[85] Pfund, A. H. Phil. Mag., 1904, *7*, Ser. 6, pp. 26-39.

[86] Sale. Proc. Roy. Soc. of London, 1873, *21*, pp. 283-285.

[87] Adams and Day. Philos. Trans., 1877, *167*, pp. 313-349.

[88] Bell, G. Nature, 1878, *22*, p. 500.

[89] Bidwell, S. *Loc. cit.*

copper; Pfund[90] and Berndt,[91] carbon. Dieterich[92] tried copper, nickel, platinum, German silver and Advance wire. He found that copper, German silver and Advance wire have the disad-vantage that at the temperature of annealing a film of oxide is formed. This so materially increases the resistance of the cell is to make it practically useless except with very sensitive auxili-ıry apparatus. Nickel wire is much less easily oxidized and)roved as satisfactory as platinum wire besides being less ex-)ensive. Pfund and Berndt consider carbon electrodes prefer-ıble in that selenium forms no conducting compound with car-)on. On the question of size of electrodes, there seems to be eneral agreement that large surface contact between the junc-ions and the selenium is necessary to avoid high junction resist-nce and consequent diminished sensitivity of the cell.

d. *Strength of the battery current.* The sensitivity of the elenium cell has been found to vary with the battery current. It as first noted by Adams and Day[93] that the resistance of selenium iminished as the battery current is increased. Sabine[94] held this) be true only after a certain intensity of current had been ached. For lower intensities of current, increase of current ıused increase of resistance. Minchin[95] increased the conduc-vity of his cell fourfold by increasing the voltage from 2 to 12)lts. Brown[96] found that with a Ruhmer cell the conductivity ıried by an amount almost directly proportional to the voltage; ith a Giltay cell, however, the variation decreased in amount as e voltage was increased. Ries[97] claims that conductivity in-eases with increase of voltage for a range of from 0.4 to 4 lts. Luterbacher[98] states that this change is greater for direct an for alternating current. The necessity for an accurately

[0] Pfund, A. H. *Loc. cit.*
[1] Berndt, G. *Loc. cit.*
[2] Dieterich, E. O. Phys. Rev., 1914, *4*, Ser. 2, p. 468.
[3] Adams and Day. *Op. cit.*, p. 319.
[4] Sabine, R. Phil. Mag., 1878, *5*, ser. 4, pp. 401-416.
[5] Minchin, G. M. Phil. Mag., 1891, *31*, ser. 5, pp. 207-238.
[3] Brown, F. C. *Loc. cit.*
[7] Ries, C. Phys. Zeit., 1911, *12*, p. 529.
[3] Luterbacher, J. Ann. der Physik, 1910, *33*, p. 1392.

constant battery current when using a selenium cell as a measuring instrument is obvious.

e. *The direction of the battery current.* Adams and Day[99] found that the passage of a current in any direction at any period in a series of observations produces a condition which tends to facilitate the subsequent passage of a current in the opposite direction but obstructs one passing in the same direction. He interprets this condition as a slight "set" of the molecules. The effect is particularly marked in case of the first current sent through the selenium and is more or less permanent. This result was confirmed by Sabine[100] who thinks the changes are in the resistance of both the selenium and the junctions. This fact combined with the changes in resistance caused by changes in the strength and duration of current led Sabine to state that selenium is very unsuitable for the production of a constant resistance for measuring purposes.

f. *Duration of battery current.* Adams and Day[101] found that the resistance of selenium increases continuously during the time of the passage of the battery current. They point out, for example, that on this account the precaution should always be taken to shut off the current between observations. This precaution, however, does not eliminate; it only lessens the effect of the variable factor.

g. *Temperature.* Bidwell[102] claims that there is an optimum temperature for each cell above and below which the resistance decreases. For six cells this temperature was 24, 23, 14, 30, 25 and 22° C. Brown and Stabbins[103] tested the effect of temperatures ranging from 40° to 200° C. and found that the resistance of selenium decreases with increase of temperature. Temperatures above or below these were not used, so their results contain nothing that bears directly on the claim made by Bidwell. For a change of temperature ranging from 13.2° to 73.4° C. they found that a given amount of light incident on the cell caused changes of

[99] Adams and Day. *Op. cit.*, p. 323.
[100] Sabine, R. *Loc. cit.*
[101] Adams and Day. *Op. cit.*, p. 314.
[102] Bidwell, S. Phil. Mag., 1881, *11*, Ser. 5, p. 302; 1895, *40*, ser. 5, p. 242.
[103] Brown and Stebbins. Phys. Rev., 1908, *26*, pp. 273-298.

resistance varying in percentage from 24.9 to 3.7. The effect of temperature on the sensitivity of the cell is so marked that Pfund, for example, worked in a room in which the temperature was kept constant to 1/10°.

h. *Pressure.* According to Brown,[104] Brown and Stebbins,[105] and Montén,[106] increase of pressure decreases the resistance of selenium and lowers its sensitivity to light. Brown found that these effects were present up to a pressure of 1,000 atmospheres. In case of a single crystal of selenium, he increased the conductivity about 120 times by an increase of pressure of 180 atmospheres. Brown and Stebbins found the percentage change of resistance for one atmosphere to vary between 0.05 and 0.30 for different cells.

i. *Moisture.* Ries,[107] Bidwell[108] and others have shown that humidity affects the electrical properties of selenium. Ries thinks his effect is sufficient to explain the discrepancies existing in the esults of different observers. On this account cells of the Giltay ype, which are constructed so that there is free communication etween the outer air and the selenium surface, show wide variaons in conductivity. Nicholson[109] improved the constancy of a ell of this type by enclosing it in an air-tight box with a glass indow.

j. *Age of cell.* Adams and Day[110] found the sensitivity of the lenium cell to be greatly reduced after one year. Bidwell[111] und no material loss at the end of one year, but the cells were actically useless after four years. Dieterich,[112] however, conucted two cells of remarkably high sensitivity which lost ⅘ of eir sensitivity within a month.

[104] Brown, F. C. Phys. Rev., 1905, *20*, pp. 185-186; Phys. Rev., 1914, *4*, . 2, pp. 85-98.

[105] Brown and Stebbins. *Loc. cit.*

[106] Montén, F. Ark. för. Mat. Astron. och. Fysik, Stockholm, 1908, *4*, 1-6.

[107] Ries, C. Phys. Z., 1908, *9*, pp. 569-582.

[108] Bidwell, S. Phil. Mag., 1895, *40*, ser. 5, p. 245.

[109] Nicholson, P. J. Phys. Rev., 1914, *3*, Ser. 2, p. 8.

[110] Adams and Day. *Op. cit.*, p. 348.

[111] Bidwell, S. Phil. Mag., 1891, *31*, Ser. 5, pp. 250-256.

[112] Dieterich, E. O. Phys. Rev., 1914, *4*, Ser. 2, p. 471.

k. *The amount of polarization gradually set up in the cell.* The presence of polarization currents produced by the passage of a battery current though selenium was found by Adams and Day.[113] This effect was increased by the exposure of the selenium to light. Bidwell[114] says the polarization current is very troublesome in making accurate resistance tests by the bridge method. The intensity of this current is increased by humidity. While this factor and the next to be considered, the presence of photo-electric currents, can hardly be said to influence the sensitivity of the cell in a way similar to the preceding factors, they undoubtedly affect its use as a light-measuring instrument; for with the presence of polarization and photo-electric currents of unknown intensity, an exact determination of the conductivity of the cell under a given set of conditions can not be made.

l. *Photo-electric currents.* The presence of photo-electric currents in selenium due to an exposure to light was noted first by Adams and Day,[115] later by Bidwell [116] and by Minchin.[117] Adams and Day found that this current was often more intense than the polarization current and was sufficient to overbalance a weak battery current.

2. *Factors which render it difficult to use the selenium cell for quantitative work either as an ohmic resistance or as a light-measuring instrument.*

A part of the foregoing factors are of importance chiefly in making it almost impossible to construct two selenium cells of similar properties. They do not affect the use of a given cell once constructed. The remainder, however, apply to the responses of a single cell and are so difficult if not impossible of control as to make it exceedingly doubtful whether the selenium cell can be used as an instrument of precision. In fact the consensus of opinion among the investigators has been that it can not be used with a degree of precision which is acceptable in quantitative

113 Adams and Day. *Op. cit.*, p. 328.
114 Bidwell, S. Phil. Mag., 1895, *40*, Ser. 5, p. 244.
115 Adams and Day. *Op. cit.*, p. 333.
116 Bidwell, S. *Op. cit.*, p. 251.
117 Minchin, G. M. Phil. Mag., 1891, *31*, Ser. 5, pp. 207-238.

work. These factors are: (1) The passage of the battery current through the cell in a given direction produces a condition which tends to facilitate the subsequent passage in the opposite direction, but obstructs one in the same direction. Since this effect can not be completely eliminated and the cell restored to its original condition by reversing the current, the cell continually changes its state of conductivity with use; hence two measurements can never be made with it in the same condition. This lifficulty is further increased by the fact that the longer the curent is allowed to flow, the greater is the change of conductivity. The greater number of times the cell is used, therefore, and the onger the current is allowed to flow, the greater will be the rogressive change in the properties of the cell. (2) Over and bove the effect of current is a loss of sensitivity with age. leasurements made by the cell at intervals at all widely separated e, therefore, not comparable. (3) The polarization currents ie to the passage of the battery current and increased by the posure to light, and the photo-electric currents which are even ronger than the polarization currents and strong enough accordg to Adams and Day to overcome a weak battery current, proice a variability in the action of the cell for which there seems be no remedy. When to these apparently insuperable obstacles added the fact that the strength of the battery current, the nperature of the cell and the humidity of the atmosphere must kept constant within small limits, one gets some idea of the ficulties attendant on the use of the selenium cell as an instrunt of precision.

3. *Factors which apply especially to its use as a light measur- instrument.* The foregoing properties of selenium, it may be ed, apply to its use as material for the construction both of nic resistances and of instruments for the measurement of t. In addition to these the following points which apply ifically to its use in the measurement of light are to be sidered.

The preexposure of the cell. Adams and Day[118] claim that

[118] Adams and Day. *Op. cit.*, p. 315.

selenium is more sensitive in its response to light after it has been kept in the dark for several hours than after it has been exposed to light several times; hence the result obtained from the first of a series of measurements is generally not comparable with those gotten later. Townsend[119] says that after prolonged exposure to light there is a fatigue effect which takes place immediately and lasts at least four hours. Nicholson[120] says that fatigue effects are present when the cell has not been allowed sufficient rest between readings. Marc[121] finds that the sensitivity to red light is greatly modified by a previous strong illumination with white light or by a long continued blue illumination. Grantham[122] investigating the recovery period of the cell, found that for a short time after the exposure to light was cut off, the resistance decreased still further; it then increased rapidly at first, then more slowly. After constant use the cells became at times temporarily almost insensitive.

b. *The time of exposure to light.* For Pfund[123] a maximum response was reached in 2 to 3 sec.; then a slight "creeping effect" took place. In later work he[124] used an exposure time of 12.5 seconds. Brown[125] claims that the change of conductivity is a function of the time of illumination. For effect of exposure time on response to monochromatic light, see pp. 35-36.

c. *The wave-length of the spectrum light and the factors which influence the selectiveness of response to wave-length.* Sale[126] was the first to report that selenium is selective in its response to wave-length. He found the greatest change in resistance was caused by red light near the end of the solar spectrum; next by red of shorter wave-length; then in order by orange, green, blue and violet. Adams and Day[127] found th

119 Townsend, F. *Loc. cit.*
120 Nicholson, P. J. *Op. cit.*, p. 9.
121 Marc, R. Z. Anorg. Chem., 1903, *37*, pp. 459-475.
122 Grantham, G. E. Phys. Rev., 1914, *4*, Ser. 2, pp. 259-266.
123 Pfund, A. H. Phil. Mag., 1904, *7*, Ser. 6, pp. 26-39.
124 Pfund, A. H. Phys. Rev., 1912, *34*, p. 370.
125 Brown, F. C. Phys. Rev., 1911, *33*, pp. 14-15.
126 Sale. Proc. Roy. Soc. of London, 1873, *21*, pp. 283-285.
127 Adams and Day. *Op. cit.*, p. 317.

reatest light effect in the greenish yellow, next in the red and ast in the violet. Pfund[128] used lights equalized in energy by a ermopile and later by a radiomicrometer. He got the maximum sponse near .7μ. This maximum was not changed when selen-es of lead, mercury, copper, and silver were introduced. Brown d Sieg[129] found the curve of response to wave-length to vary r different types of cell. With reference to selectiveness of re-onse to wave-length two sorts of investigation have been made, one to determine the factors that influence this selectiveness in given cell; the other to determine the factors which influence ectiveness in different cells.

(1) *Factors which have been found to influence the selective-ss of response for a given cell.* The following factors have en found to influence the selectiveness of response in a given l.

(a) *Intensity.* Pfund[130] found the sensitivity curve for wave-gth to vary with the intensity of the incident light. This was firmed by Brown and Sieg[131] and by Nicholson.[132] With ref-nce to the changes in the sensitivity curve Pfund contributes following formula: $d=DI^{\beta}$ where d= change of conductiv- I= energy of illumination; and D and β are constants depen-t on the wave-length of the incident light. For exposures of ; sec., he found D to be constant for any particular wave-th; β was very nearly ½ for regions of the spectrum from violet to the yellow; but its value increased as red was ap-ched, equalling 1 for deep red and infra-red. Nicholson fied both the formula and the constants for an exposure time 2.5 sec.

) *Length of exposure time.* Nicholson,[133] however, found formula contributed by Pfund to hold only for an exposure of 12.5 sec. For longer and shorter exposures, the value of anged. For 10 sec. exposure, it increased and the region in

Pfund, A. H. Phil. Mag., 1904, *7*, Ser. 6, pp. 26-39; Phys. Rev., 1909, . 324-336.
Brown, F. C. and Sieg, L. P. Phys. Rev., 1914, *4*, Ser. 2, pp. 48-61.
Pfund, A. H. Phys. Rev., 1909, *28*, pp. 324-336.
Brown, F. C. and Sieg, L. P. Phys. Rev., 1913, *2*, Ser. 2, pp. 487-494.
Nicholson, P. J. Phys. Rev., 1914, *3*, Ser. 2, pp. 1-24.
Nicholson, P. J. *Loc. cit.*

which β becomes 1 shifted towards the shorter wave-lengths. With longer exposures (15 to 20 sec.), the value of β decreased. With unlimited exposures or until a steady state of resistance of the selenium was attained, β equalled 0.5 throughout the spectrum, except at about 600$\mu\mu$ where it equalled only 0.4. This change in the value of β for different wave-lengths with exposure time is probably in accord with Nicholson's further demonstration that selenium has a different inertia of response for different wave-lengths. This is particularly marked for the red and infra-red of the spectrum. Brown and Sieg[134] also note a change in the shape of the sensitivity curve for exposures of 30 and 0.4 sec.

(c) *Temperature, humidity and voltage.* That the selectiveness of response of selenium to wave-length varies with the temperature of the cell is mentioned by Marc[135] and Nicholson;[136] Marc finds it to vary also with the intensity of the current used and Nicholson with the humidity.

(d) *Photo-electric currents.* Minchin[137] using seleno-aluminium cells, found that the intensity of electromotive force produced by the action of light on the cell varies with the wave-length of the incident light. It is greatest in order for yellow, orange green, red and blue.

(2) *Factors which have been found to influence the selectiveness of response to wave-length in different cells.* The main cause of difference in the selectiveness of response to wave-length from cell to cell is according to Brown and Sieg[138] and to Dieterich[139] the temperature at which the cell was made and annealed. In general there are two groups of cells,—those with the maximum response at wave-lengths greater than 640$\mu\mu$; and those with the maximum at a wave-length less than this. Cells of the former group are produced by annealing at lower temperatures e.g., annealing at 170° C. gives a pronounced red maximum

134 Brown and Sieg. Phys. Rev., 1913, *2*, Ser. 2, pp. 487-494.
135 Marc, R. Z. Anorg. Chem., 1903, *37*, pp. 459-475.
136 Nicholson, P. J. *Loc. cit.*
137 Minchin, G. M. Phil. Mag., 1891, *31*, Ser. 5, pp. 207-238.
138 Brown, F. C. and Sieg, L. P. Phys. Rev., 1914, *24*, Ser. 2, pp. 48-61.
139 Dieterich, E. O. Phys. Rev., 1914, *4*, Ser. 2, pp. 467-476.

iose of the latter group by annealing at high temperature, *e.g.*, at ro° C. By partial annealing at 210° and completing the process a lower temperature, the maximum response is given in the ue and a secondary maximum in the red. Brown[140] confirms is result with his selenium "crystal forms" produced by the blimation of the vapor either in a high vacuum or at atmoseric pressure. Among these forms he finds types which ve the different wave-length sensitivity curves found by eterich in the different cells annealed at the various temperares. Brown believes that there are at least three forms of tallic selenium of widely different electrical resistivity. These rms are produced at different temperatures. That is, at high nperatures, for example, crystals of maximum sensitivity to l light are not allowed to form.

1. *The intensity of white light.* Attempts have been made to the selenium cell both as a radiometer and a photometer. In latter case, the following laws of change of resistance with nge of intensity have at different times been formulated. ien m= conductivity, i= light intensity, R= resistance, and other quantities are constants, Rosse,[141] Adams and Day,[142] Berndt[143] give the formula $i = cm^2$; Hopius,[144] $i = cm^3$; ianasiadis,[145] $i = m(m-a)b$; Hesehus,[146] $i = b^m - 1$; Ruhmer,[147] $R_b = (b/a)^a$; Stebbins, $i = cm$. (See Brown, Phys. Rev., 1, *33*, pp. 1-26.) Brown states that although the illumination l, time of exposure, and construction of cell varied in the k of the above men, it appears obviously futile from these lts to look for a universal law of conductivity for the selenium as a function of intensity of illumination.

1 summarizing the difficulties that apply to the use of the

Brown, F. C. Phys. Rev., 1914, *4*, Ser. 2, pp. 85-98; see also Dietrich, p. 474.
Rosse. Phil. Mag., 1874, *47*, Ser. 4, pp. 161-164.
Adams and Day. *Op. cit.*, p. 318.
Berndt, G. Phys. Z., 1904, *5*, pp. 121-124.
Hopius. Jurn. Russk. Fisik Chimicesk. Obscestva, 1903, *35*, pp. 581-585.
Athanasiadis, G. Ann. der Physik, 1908, *25*, pp. 92-98.
Hesehus, N. A. Jurn. Russk. Fisik. Chimicesk. Obscestva, 1905, *37*, 21-231; Phys. Zeit., 1906, *7*, pp. 163-168.
Ruhmer, E. Phys. Zeit., 1902, *3*, pp. 468-474.

selenium cell in the measurement of light, the following points then may be noted. (1) The fatigue effects and the effects of previous exposure to light are so great that it is exceedingly difficult to keep the cell in a state of constant sensitivity (2) The amount of response is not only a function of the time of exposure to the light, but apparently rather complexly so. (3) There is not only selectiveness of response to wave-length but the amount of this selectiveness varies with the intensity of light, with the strength of the battery current, with the temperature of the cell and with humidity.[148] While there is a possibility of controlling the last three of this latter group of factors, there seems no way to deal satisfactorily for any wide use of the cell with the first, or what may be termed roughly a "Purkinje phenomenon." Because of this factor a calibration of the cell for wave-length for one intensity of light would not hold for all intensities, which would limit the use of the cell to the intensity of light for which it was calibrated or for ranges for which there is no change in relative sensitivity to wave-length. That is, any wide use of the cell would require both a wave-length and an intensity calibration in terms, for example, of the responses of the non-selective instruments. And (4) there seems to be no regular relation of the amount of response to the amount or intensity of light used even when the lights are of the same composition. At least according to Brown this is the conclusion that must be drawn from the work that has been done with white light. If this be true, the possibilities of use of the selenium cell as a radiometric instrument seem in general practice to be limited to the equalization of light intensities and this, unless correction factors are used, only in case the lights are of the same composition. In this regard its case is similar to that of the eye when considered as a possible radiometric instrument.[149]

148 It will be remembered also that the intensity of the photo-electric currents that are set up by the action of light on selenium which are an important factor in the variability of action of the cell, are different for the different wave-lengths. This factor obviously can not be controlled and there seems no satisfactory calibration for it.

149 In this lack of a simple relation between the amount of intensity of light and amount of response, the selenium cell again presents an analogy to

4. *Theories of the action of light on selenium.* It may be of interest to append here a brief account of the theories that have been advanced to explain the action of light on selenium. The change of resistance of selenium under the action of light has at various times been thought to be a heating effect, to be electrolytic in nature, to be electronic, or to be of chemical origin. The first view was held by Sale, Sabine and Moser. Sabine, for example, thought that the action is similar in character to that of a dielectric "more or less charged with conducting crystals." In such a case the light by its heating effect would modify the surface tension of the selenium, which modification would probably cause an expansion of its crystalline surface and this in turn would result in a closer contact among the superficial crystals. This view was disproved by the demonstration that the light effect of the different wave-lengths on selenium does not correlate with their heating effect.

The theory that the action is electrolytic was first proposed by Adams and Day. They did not claim that actual electrolysis takes place, however, but that the molecular structure or crystalline condition of the selenium is altered or modified by the action of a current of electricity in such a manner as to produce effects analogous to those which would occur if the selenium were an electrolyte and were actually decomposed by the current. Furthermore, they thought that the action of light falling on selenium is to promote crystallization and thus to diminish its resistance to an electric current, inasmuch as in changing to the crystalline state selenium becomes a better conductor of electricity. And as this crystallization is greatest in the exterior layers of the

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the eye. And as in case of the eye this relation has as yet proven incapable of mathematical formulation. Fechner in his attempt to give a mathematical expression of the relation between stimulus and response for sensation in general was only trying to do what a number have tried to do with regard to this reaction both of the selenium cell and the photographic plate. When one knows how signally the attempt to find an expression separately for either of these reactions has failed, one realizes still more clearly the *a priori* improbability of finding a single expression that will apply to the reactions of five sensory mechanisms so differently constituted as they seem to be.

selenium, a flow of energy from within outwards is produced which under certain circumstances appears to produce an electric current (the photo-electric current). Bidwell thought the action is really electrolytic, impure selenides having been used or selenides having been formed between the selenium and the metallic electrodes.

Bidwell's view was disproved by Pfund and later by Berndt, both of whom used purified selenium and carbon electrodes and got greater sensitivity to light with the purified than with the impure selenium. Pfund developed an electronic theory of the action, an explanation that had previously been suggested by Nagaoka. He considered the effect due to a resonance of the electrons in the atom under the action of light, causing explosions which lead to an increase in the number of conducting electrons. There is, moreover, a "critical depth" of penetration above and below which the action on selenium is less pronounced. This fact accounts for the selective response to wave-length of light, the maximum response being to that light which penetrates to the "critical depth"; also for the change in this selectiveness of response to wave-length with change of intensity of the incident light. This view is held also by Ries and Nicholson.

The chemical theory has been followed among others by Marc, Montén, Kruyt, Pochettino and Berndt. These men have obtained evidence that leads them to believe that there exist at least two forms of metallic selenium of widely different electrical resistivity, and they assume that illumination brings about a transformation from the less to the more conductive of the two.

Brown claims to have found and isolated three forms of selenium crystals. They are produced at different temperatures in the annealing process and possess different conductivity. These "crystal forms" have also a different selectivity of response to wave-length. In his opinion the character of the conductivity curves for the four known varieties of light-sensitive selenium can be explained by assuming the existence of three components in dynamic equilibrium under a given illumination, temperature, pressure and electrical potential difference. Any agency that changes

the conductivity of selenium is of such a nature that it alters the rate of interchange between these components.

F. The photo-electric cell.

The action of the photo-electric cell depends upon the effect of light on the capacity of certain metals to hold a negative charge of electricity. Knowledge of the action of light on the conduction of electricity goes back to the discovery by Hertz in 1887 that the incidence of ultra-violet radiations on a spark gap facilitates the sparking. This led to a general investigation of the effect of light on the conduction of electricity.[150] The discoveries which paved the way directly for the invention of the photo-electric cell were those pertaining to the effect of light on the electrical condition of certain metals. It was found, for example, that a zinc plate exposed to light becomes slightly positively charged; that a negatively charged plate becomes less negatively charged; and that a positively charged plate is not affected. Later studies showed that the electrical condition of all metals is changed to some extent by the action of light. Those affected most are, according to Elster and Geitel,[151] rubidium, potassium, alloy of potassium and sodium, sodium, lithium, magnesium, thallium, and zinc.

The essential parts of the photo-electric cell are as follows. There must be juxtaposed in a glass tube or vessel a negatively charged surface of the metal in question (the cathode) and a conductor or anode to receive the charge as it is lost by the cathode under the action of light. Connected in series with the cell is either an electrometer or a galvanometer. In some cases the inside of the cell is coated with the metal forming the cathode and a receiving wire is suspended in the cell. In others, the negatively charged metal is suspended in the cell and the body of the tube silvered on the inside serves as anode. The photo-

[150] See Hallwachs, W. Ann. der Phys., 1888, *33*, p. 301; Hoor, M. Repertoire des Physik, 1889, *25*, p. 91; Righi, A. Comptes Rendus, 1888, *106*, p. [illegible]9 and *107*, p. 559; Stoletow, A. *ibid.*, 1888, *106*, p. 1149, 1593 and *107*, p. 91; [illegible]9, *108*, p. 1241; Physikalische Revue, Stuttgart, 1892, *1*.

[151] Elster, J. and Geitel, H. Nature, 1894, *50*, p. 451.

electric current may be measured in five ways: (1) by the rate of drift of an electrometer needle; (2) by the ballistic method or the measurement of the charge acquired in a definite exposure time by an electrometer connected with the cell; (3) by measuring the potential across the terminals of a high resistance in series with the cell; (4) by balancing the photo-electric current with a current variable in a known manner, by means of either an electrometer or a sensitive galvanometer; and (5) by the deflections of a sensitive galvanometer. Ives[152] commenting on these recommends the third method. He finds the first inadvisable because the rate of drift is not uniform; the second, because the deflection varies with the exposure time; and the fifth, because it is insensitive.

1. *Factors that have been taken into account in the construction and use of photo-electric cells.* The following are some of the factors that have been taken into account in the construction and use of sensitive cells.

a. *The metal used.* The metal used should have a high emissive power and should permit of a certain ease in handling. Different metals have been used by different experimenters. Compton and Richardson,[153] for example, used aluminium, platinum, sodium and caesium. Potassium and sodium have been most frequently employed. For a summary of the metals used by different investigators, see Allen, Photo-electricity, 1913, p. 68.

b. *The residual gas.* It is desirable of course to have for the residual gas one which ionizes easily but not to such an extent that the recombination of the ions is measurable, also one which is easy to handle. Elster and Geitel[154] tested the rate of loss of charge from an illuminated surface through air, carbon dioxide, oxygen and hydrogen; and found that the rate of leak through carbon dioxide was much faster than for any of the other gases. Hydrogen, helium or argon have been most frequently used in the more recent work with photo-electric cells.

152 Ives, H. E. Astrophys. Jour., 1914, *39*, p. 428.

153 Compton, K. T. and Richardson, O. W. Philos. Mag., 1913, *26*, Ser. 6, p. 561.

154 Elster, J. and Geitel, H. Ann. der Phys., 1890, *41*, p. 166.

c. *The pressure of the residual gas.* There are two factors ιere which work against each other. If we consider the current from the cathode to the suspended loop of wire as the discharge of negative electrons from the cathode, a vacuum would offer the east impedance. An advantage is gained, however, by adding to he electrons sent off by the metal, electrons freed by ionizing the gas in the tube. The effect of pressure on the intensity of the photo-electric discharge has been investigated by Stoletow,[155] Schweidler[156] and Kemp[157] by comparing the intensity of the urrent for different pressures under otherwise constant condiions. For Stoletow the most favorable range of pressures is rom 0.275-2.48 mm.; for Schweidler, from 1-2 mm.; for Kemp, rom 2-3 mm. In a recent work Ives, Dushman and Karrer[158] ound that the pressure giving the greatest sensitivity varies with ιe voltage; further that the "photo-electric sensitiveness does not isappear when the metal is made as gas-free as possible and the egree of vacuum is made as high as possible."

d. *The potential difference between anode and cathode.* There ιust be a sufficient difference of potential between anode and ιthode to guarantee that all of the electrons are drawn) the anode, *i.e.*, there must be a saturation difference of otential. The difference must not, however, be so great as to ιuse sparking, and it must be kept fairly constant. From about) to 180 volts are generally used. For an investigation of this fect, see Stoletow[159] and Schweidler.[160]

e. *The galvanometer or electrometer.* The electrometer is ore sensitive than the galvanometer, but it is so much harder to anage that it seems to be the general opinion that it should be ed only for measuring very low intensities.[161]

155 Stoletow, A. Comptes Rendus, 1888, *107*, p. 91; J. de Phys., 1890, *9*, 468.

156 Schweidler, E. R. Sitzungsber. der Wien. Akad., 1898, *107*, 2a, p. 881.

157 Kemp, J. G. Phys. Rev., 1913, *1*, Ser. 2, p. 274.

158 Ives, Dushman and Karrer. Astrophys. Jour., 1916, *43*, p. 9.

159 Stoletow, A. Comptes Rendus, 1889, *108*, p. 1241.

160 Schweidler, E. R. *Loc. cit.*

161 See Richtmyer, F. K. Transactions Illuminating Engineering Society, 13, *8*, p. 461.

f. *The angle of the incident light.* Elster and Geitel[162] first reported that the angle at which the light strikes the cathode plate causes a difference in the effect on the plate. This effect has been investigated among others by Pohl[163] and Kunz.[164] Elster and Geitel claim to have overcome the effect due to angle of incidence by using a diffusing screen so that the light falls equally at all angles on the plate.[165] Pohl and Pringsheim[166] have found in addition that the curve of selective response to wave-length of the photo-electric cell varies with the angle of incidence.

g. *Dark effects and after-effects.* When a cell is charged and left in the dark, a slight leakage or discharge is found to take place which is increased following an exposure to light. This leakage Elster and Geitel[167] believe to be due to a conduction of current over the surface of the glass from the cathode to the anode circuit. In any event guard rings of metal connected to earth, placed on the inside and outside of the tube between the cathode and anode circuit, completely eliminated the leakage.

h. *Fatigue effects.* Some metals when freshly prepared throw off many electrons when acted upon by light, then the number becomes less. This decrease in the responsiveness of the metal is apparently rapid at first, then becomes slower, ceasing perhaps in a few days. Allen,[168] for example, measured the photo-electric activity at different intervals from 2 to 100 minutes after polishing the surface of a zinc plate. He found a decrease in activity which was rapid for the first few minutes, then more gradual after 20 to 30 minutes. Sadzewicz[169] reports a similar result. The effect has also been investigated by Holman,[170] Hallwachs,[171]

[162] Elster, J. and Geitel, H. Wied. Ann. der Phys., 1894, *52*, p. 433; 1895, *55*, p. 684; 1897, *61*, p. 445.

[163] Pohl, R. Phys. Z., 1909, *10*, p. 542.

[164] Kunz, J. Phys. Rev., 1909, *29*, p. 174.

[165] Elster, J. and Geitel, H. Phys. Z., 1912, *13*, p. 740.

[166] Pohl, R. and Pringsheim, P. Deutsch. Phys. Gesell., 1910, *12*, p. 215.

[167] Elster, J. and Geitel, H. Phys. Z., 1913, *14*, p. 741.

[168] Allen, H. S. Proc. Roy. Soc., 1907, *78*, Ser. A., p. 483.

[169] Sadzewicz, M. Acad. Sci. Cracovie, Bull., 1907, *5*, p. 497.

[170] Holman, W. F. Phys. Rev., 1907, *25*, p. 81.

[171] Hallwachs, W. Ann. der Phys., 1907, *23*, (4), p. 459.

Compton and Richardson,[172] Buisson,[173] Ladenburg[174] and Bergowitz.[175] Bergowitz claims, however, that there is no fatigue in case of cells whose negative poles are formed of alkali metals. This statement is confirmed by Elster and Geitel[176] who say: "sogenannte 'Ermüdungserscheinungen' an Alkalimetallzellen nicht auftreten." Ives, Dushman and Karrer, however, apparently found fatigue effects in potassium cells.

2. *Comparative advantages and disadvantages of the photo-electric cell.* The photo-electric cell has the advantage of comparatively high sensitivity. To offset its sensitivity, however, it has the following serious disadvantages. (a) It is selective in its response to wave-length. The shorter wave-lengths are overestimated. This selectiveness moreover, varies with the metal used in the cell. Pohl, and Pohl and Pringsheim have plotted the curves of response to wave-length for the following metals: mercury,[177] platinum and copper,[178] potassium-sodium alloy,[179] rubidium, potassium and sodium,[180] barium, [181] lithium and sodium,[182] magnesium and aluminium,[183] and calcium.[184] The selectiveness for calcium is found to be very similar to the selectiveness of the eye to wave-length. Richtmyer has plotted the curve for sodium;[185] Hallwachs for potassium;[186] Kunz for sodium-potassium alloy;[187] and Elster and Geitel for

[172] Compton, K. and Richardson, O. Philos. Mag., 1913, *26*, Ser. 6, p. 561.

[173] Buisson, A. Comptes Rendus, 1900, *130*, p. 1298; Ann. Chim. Phys., 1901, *24*, p. 320.

[174] Ladenburg, E. Ann. der Physik, 1903, *12*, p. 558.

[175] Bergowitz, K. Phys. Z., 1907, *8*, p. 373.

[176] Elster and Geitel, H. Phys. Z., 1913, *14*, footnote p. 742.

[177] Pohl, R. Phys. Gesell. Verh. 1909, *11*, p. 609.

[178] Pohl, R. *Ibid.*, 1909, *11*, p. 339.

[179] Pohl, R. *Ibid.*, 1909, *11*, p. 715; Pohl and Pringsheim; *Ibid.*, 1910, *12*, p. 215, 349, 682, 697.

[180] Pohl and Pringsheim. *Ibid.*, 1910, *12*, p. 1039; 1911, *13*, p. 219.

[181] Pohl and Pringsheim. *Ibid.*, 1911, *13*, p. 474.

[182] Pohl and Pringsheim. *Ibid.*, 1912, *14*, p. 46.

[183] Pohl and Pringsheim. *Ibid.*, 1912, *14*, p. 546.

[184] Pohl and Pringsheim. *Ibid.*, 1913, *15*, p. 111.

[185] Richtmyer, F. K. Phys. Rev., 1910, *30*, p. 385.

[186] Hallwachs, W. Ann. der Phys., 1909, *30*, (4), p. 593.

[187] Kunz, J. Phys. Rev., 1909, *29*, p. 212.

rubidium, potassium and sodium.[188] (b) Griffith[189] working with ultra-violet light, and Dember[190] working with the visible spectrum, both claim that it is also selective in its response to intensity. That is, they do not find a constant relation between intensity of radiation and photo-electric current. Elster and Geitel,[191] however, found on the other hand a constant relation between intensity of light and the response of the cell except in case of very intense light. As source they used the light of the sun, a mercury arc, a Nernst lamp of 32 cp. and a 2-volt carbon lamp. A variable resistance was used with the 2-volt lamp; also in a part of the work its light was passed through a blue filter. Richtmyer[192] found the photo-electric current from a sodium surface under the action of light from an incandescent lamp to be proportional to the intensity of the incident light for very low intensities (0.007 candle-foot) up to 620 candle-feet. Ives in 1914 found that the relation between illumination and photo-electric effect is not linear and differs from cell to cell. In 1916, however, working with Dushman and Karrer he reports that the cause of these varied relationships lies in "focusing effects." "By this term is meant a change of direction of the electron stream as the number emitted changes, whereby a different proportion of the whole number of electrons reaches the receiving electrode" (p. 25). For the elimination of these effects he recommends a cell of special construction having absolutely no free surfaces on which electric charges can collect (see p. 30). This cell, he finds, gives a rectilinear relationship between intensity of illumination and photo-electric effect.[193] (c) The cell is not sensitive to

188 Elster and Geitel. Ann. der Phys., 1894, *52*, (3), p. 438.

189 Griffith, I. Phil. Mag., 1907, *14*, (6), p. 297.

190 Dember, H. Ber. d. kgl. sächs. Akad. d. Wiss., 1912, *64*, p. 266.

191 Elster and Geitel. Phys. Z., 1913, *14*, p. 741; 1914, *15*, p. 610.

192 Richtmyer, F. K. Phys. Rev., 1909, *29*, p. 71, 404.

193 Kunz recently reports an investigation of cells of special construction the responses of which to white light for a wide range of intensities deviates so little from a linear function of intensity of light as to permit of the use of the cell for many photometric purposes. He verifies Ives's claim that in case of the older spherical form of cell, the photo-electric current is not proportional to the intensity of light. He found also that the Talbot-Plateau law holds for the responses of the cells described. (Astrophysical Jour., 1917, *45*, pp. 69-88.)

heat radiations, hence can not be calibrated against the total of radiation of a black body. The value of its responses in terms of energy units can be determined feasibly and conveniently only by the aid of some other radiometric instrument which responds to the total of radiation, *e.g.*, the thermopile, the bolometer, the Nichol's radiometer, etc. (d) With the present knowledge and control of the factors which influence its sensitivity, the cell can scarcely be recommended as giving results with a degree of reproducibility which is entirely satisfactory. Thus from the standpoint both of reproducibility and selectiveness of response the use of the cell in its present stage of development even as an energy comparator of the visible radiations can scarcely be considered as advised by the radiometric specialist. However, the cell is still being developed and perfected and may yet be of service in measuring light intensities.

As a light measuring instrument the photo-electric cell has the following advantages. (a) It has a comparatively high sensitivity especially to the shorter wave-lengths.[194] And (b) it responds very quickly to the light stimulus. Richtmyer claims, for example, that one of the special fields in which the cell promises to be serviceable is for exposures too short for the eye to be used with accuracy and convenience.[195]

G. The photographic plate.

1. *The blackening of the plate and the factors which influence this action.* When light acts on a photographic plate a chemical change takes place in the sensitive film which renders it opaque to light when the plate has been developed. This is called the blackening of the plate, and is the response that must be calibrated if the plate is to be used as a light-measuring instrument. Unlike

[194] The shape of the curve representing the photo-electric response to wave-length is for calcium very similar to that of the eye. The maximum for most of the other metals that have been investigated, occurs much nearer to the violet end of the spectrum. The position of this maximum, as has been stated above, depends on the kind of metal used to give the photo-electric effect.

[195] Richtmyer claims advantage for the cell only in certain special fields of work. (See. Trans. Illuminating Eng. Soc., 1913, *8*, p. 459.)

the thermopile, for example, which gives its maximum response when once a thermal equilibrium has been attained and is from then on practically independent of the time of exposure to the light, the blackening of the photographic plate is a function of the time of exposure to the light as well as of its intensity and wave-length. An important problem in calibrating has been, therefore, to find out whether the amount of blackening sustains any regular relation to these two factors. If so, the relation can be expressed in terms of a formula; if not, the calibration must at every point be empirical. With regard to the degree of regularity of the blackening there has been a great deal of disagreement. In 1862, for example, Bunsen and Roscoe announced that the blackening may be expressed by the formula $S=i\ t$, in which S represents the blackening, i the intensity of light and t the time of its action on the plate.[196]

[196] That equal amounts of blackening are always produced by equal intensities of light and equal times of exposure was first accepted as a theoretical principle by Malaguti (Ann. de Chemie et de Phys., *26*, p. 5; Pogg. Ann. der Phys., 1840, *49*, p. 567).

It was first experimentally demonstrated within a narrow range of light intensities (1 to 2½ in an arbitrary scale) by Hankel (Abhandl. der k. Sächs. Gesell. d. Wiss. z. Leipzig, 1864, *9*, p. 55). Its first claim to establishment as a general law came from Bunsen and Roscoe (Annal. der Phys. und Chemie, 1862, *117*, pp. 529-562). They say: "So wird man den Satz als feststehend betrachten dürfen, dass innerhalb sehr weiter Gränzen gleichen Producten aus Lichtintensität und Insolationsdauer gleiche Schwärzungen auf Chlorsilberpapier von gleicher Sensibilität entsprechen." The law may be applied under the following conditions. "(1) Wenn die bei Messungen des gesammten Himmelslichts in Betracht kommenden Lichtstärken nur noch von so kurzen Inductionsphänomenon begleitet sind, dass die dadurch erzeugten Störungen innerhalb der erlaubten unvermeidlichen Beobachtungsfehler fallen; (2) wenn es möglich ist, eine photographisch sensibele Schicht von völlig constant Empfindlichkeit darzustellen; (3) wenn sich eine unveränd-liche, zu jeder Zeit und an jedem Orte leicht wieder hervorzubringende Schwärzung finden lässt, die eine sichere Vergleichung mit einer photographisch geschwärzten Fläche zulässt."

The first suggestion that photographic action may be used as a means of measuring light intensities seems to have come from Sir J. F. W. Herschel who describes an "actinograph or self-registering photometer for meteorological purposes" in Section VIII of paper "On the Chemical Action of the Rays of the Solar Spectrum on Preparations of Silver and other Substances, both metallic and non-metallic, and on some Photographic Processes (Philos. Trans., 1840, *130*, pp. 1-61); and suggests on pp. 46-47 that the photographic

This statement that the effect of the light on the plate may be xpressed by the product of the intensity and time of exposure or directly proportional to the energy of the light incident on the late, has become widely known in the subjects of Chemistry and hysiology as the Bunsen-Roscoe law. If it were true that the ackening is proportional to the energy falling upon the sensitive irface, the photographic plate could be used directly as an energy easurer and would serve as an exceedingly useful means of easuring light intensities, for it has the additional advantages great sensitivity and of integration of action through an interl of time. More recent investigations of the blackening, hower, beginning with Abney in 1874,[197] give little support to the v formulated by Bunsen and Roscoe. The blackening does not ry regularly with the intensity and time of exposure for any nsiderable range of intensities and times of exposure. It is o, as is well-known, selective in its response to wave-length and s selectiveness varies with the intensity of the light. That is, e the eye the photographic plate is selective in its response to ensity (a crude analogy to the Purkinje phenomenon) and is egular in its action through an interval of time.[198] Moreover,

e may be used to measure light. Later A. Claudet describes the "photo-phometer, an instrument for measuring the intensity of the chemical ac- of the rays of light on all the photographic preparations, and for com-ng with each other the sensitiveness of these different preparations" ilos. Mag., 1848, Ser. 3, *33*, pp. 329-335). Claudet also refers to T. B. lan who invented an instrument which he called a heliograph consisting cylinder covered with sensitized paper placed parallel to the axis of the tic, which turned to follow the sun. The object of this apparatus was et the actinic value of the sun's rays at different times in the day. The ument was improved by R. Hunt in 1845 and called by him an actino-h. In the work of these men we find the somewhat obscure beginnings e subject of actinometry which is later to compete with photometry and metry as methods of measuring light intensities.

Abney, W. deW. Philos. Mag., 1874, *48*, Ser. 4, pp. 161-165.

In addition to the above three characteristics crudely analogous to the the action on the photographic plate is said by Bunsen and Roscoe to an inertia or lag in coming to its full value. (See Pogg. Annal., 1855, . 481-516; also Photochem. Untersuch., Ostwald's Klassiker, *34*, p. 363.) e analogy in the response of the photographic plate to the optical inje phenomenon was first mentioned by Miethe, Zur Aktinometrie nomisch-photographischer Fixsternaufnahmen, Göttingen, 1889. The

the response varies with other factors which are in practice difficult to control and exceedingly troublesome if not impossible to take into account in the derivation of formulae.[199]

The tendency in fact among recent investigators has been to question whether a mathematical expression can be given to the action for any considerable range of intensities and times of exposure and to disagree widely with regard to the formula that should be used for the range of intensities and times of exposure regarded as most favorable to regularity of action. At different times the following formulae have been derived to express the action: $S = i\ t^p$ in which p represents a constant with a value of 0.86 (Schwarzchild);[200] $S = k.\ i\ t^p$ in which k and p are both constants (Leimbach);[201] $S = k.\ \log.\ i\ t^p$ (Parkhurst);[202] and $S = \log.\ (k.\ i^m\ t^n)$ in which k, m and n are all constants (Stark).[203]

The validity of the above formulae has been the subject of considerable experimental investigation. Renwick,[204] for example,

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phenomenon is discussed and tested experimentally within certain limits of difference in wave-length by Schwarzchild, (Sitzungsber. d. Wien. Akad., Math.-Naturwiss. Classe, 1900, *109*, 2a, pp. 1127-1135). Discussing the influence of the optical Purkinje phenomenon on the systematic differences in the different brightness catalogues of stars, he says: "Aber es besteht auch für die Photographie ein dem Purkinje-Phänomen ganz analoger Übelstand. Zwei verschiedenfarbige Lichtquellen, die bei einer gewissen, für beide gleichen Expositionszeit gleiche Schwärzung ergeben, erfüllen diese Bedingung nicht mehr, wenn mann die Expositionszeit ändert oder die Intensitäten der Lichtquellen im selben Verhältnisse verstärkt" (p. 1128).

[199] Blackening is said to vary with wave-length of light, with kind of plate, with process of developing, with intensity of light, with time of exposure, with temperature of plate, and with type of exposure—continuous or intermittent. With regard to type of exposure Abney (Journ. of the Phot. Soc., 1893-4, p. 63), Eder (Sitzber. d. Wiener Akad., Math-Nat. Classe, 1899, *108*, 2a, p. 1433), Englisch (Archiv. f. Wiss. Photog., 1899, 1, p. 117; 1900, *2*, p. 131), and Schwarzchild (Astrophys. Journ., 1900, *11*, pp. 92-100) all find a less effect with an intermittent than with a continuous exposure. Abney, for example, finds the retardation to be more pronounced the greater is the ratio of closed to open sector, the greater the speed of rotation employed, and the less the light intensity.

[200] Schwarzchild, K. Astrophys. Journ., 1900, *11*, pp. 89-92.

[201] Leimbach, G. Zeit. f. wiss. Photog., 1909, *7*, p. 174.

[202] Parkhurst, J. A. Astrophys. Journ., 1909, *30*, p. 33.

[203] Stark, J. Annal. der Phys., 1911, *35*, (4) pp. 461-486.

[204] Renwick, F. F. Photog. Journ.

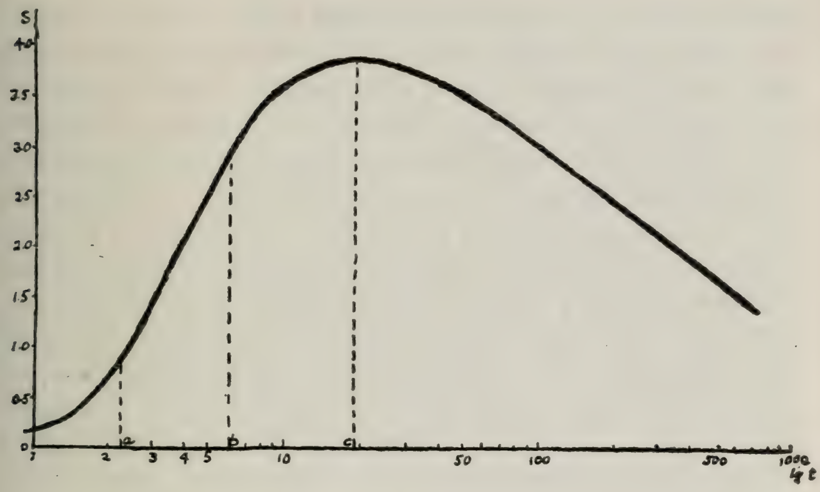


Fig. I.

contends that the Bunsen-Roscoe law falls short about 1.17 percent. Schwarzchild[205] finds for p a value of 0.86; while Tikhoff[206] claims that for the photographic rays p varies from 0.67 to 0.79; and for the green-yellow rays, from 0.91 to 0.96. Parkhurst[207] states that p is not a constant but a variable depending for its value (a) upon the density of the image, (b) the kind of plate used, and (c) the light filter employed. Geiger[208] finds that the law formulated by Schwarzchild is approximately correct within certain limits of time of action on the plate. Keeping the intensity the same and plotting the log. of the time against the blackening, Geiger obtains the curve given in Fig. 1. So plotted the curve should be a straight line according to the formula $S = i\ t^p$ if p is a constant. Between the points a and b the line is almost straight, he finds. Between these limits alone then the action is capable of approximate formulation, and the plate should not be used for light measurements for lengths of ex-

205 Schwarzchild, K. *Loc cit.*

206 Tikhoff, G. Mittheilungen d. Nikolai-Hauptsternwarte zu Pulkow, 1909, *31*, (3), p. 31; Comptes Rendus, 1909, *148*, p. 268.

207 Parkhurst, J. A. Astrophys. Journ., 1909, *30*, p. 34.

208 Geiger, L. Annal. der. Phys., 1911, *37*, (4) pp. 68-78.

posure time that do not fall within these limits. Abney[209] conducts an investigation for the special purpose of showing the dependence of the blackening upon wave-length. Stark[210] finds that k, m and n in the formula $S = \log. (k. i^m t^n)$ depend upon the wave-length; Eder[211] gets results showing that the time exponent depends upon the wave-length; while Leimbach[212] contends that both the intensity exponent m and the time exponent n are independent of wave-length. Stark[213] claims that the time exponent n is a constant for a range of light intensities from 1 to 1600 in an arbitrary scale. The intensity exponent m within this range varies 5 percent. for some emulsions and for others it varies widely. k also varies quite widely. k, m and n may be considered as constants over a range of intensities varying from 1 to 10c for the "normalbelichtung."

2. *The possibilities of using the photographic plate in quantitative work.* While the above may be considered only as the briefest mention of the quantitative work that has been done on th blackening of the photographic plate, still it is enough to show that the plate can scarcely be considered as a feasible light measuring instrument. Its quickness of response, its sensitivity and especially its integration of action through an interval o time make it very valuable, however, for many kinds of scientifi work in which quantitative comparisons are not important.

H. The eye.

1. *The two possibilities of using the eye in light measure ments.* As an instrument for the measuring or comparing o light intensities, the eye may be regarded in two ways. (1) I may be used to rate and compare lights designed for its ow service. In the production of illumination effects this is th work of photometry and should be done by the eye or some ir strument calibrated to give results in terms of the response c

209 Abney, W. deW. Proc. Roy. Sec., 1901, *68*, pp. 300-321.

210 Stark, J. Annal. der Phys., 1911, *35*, (4), pp. 461-486.

211 Eder, J. M. *Op. cit.*, p. 1473.

212 Leimbach, G. Diss. Göttingen, 1909; Zeit. f. wiss. Photog., 1909, p. 257.

213 Stark, J. *Loc. cit.*

ie eye. And (2) it may be used in balancing the energies of ghts of the same spectro-radiometric composition. Used as ich it is one of the most sensitive of the energy-comparing inruments. It can not be used, however, to balance radiometrically lights differing in composition without elaborate calibration, ecause of the degree of selectiveness of its response to wavelength.[214]

2. *The comparative advantages and disadvantages of the use the eye for balancing energies of light of the same spectrodiometric composition.* When used to balance lights of the me spectro-radiometric composition, the eye has the following vantages. (a) It is highly sensitive, among the most sensitive the light measuring instruments. (b) It is quick in its tion, reaching its maximum of response in times variously esti-

[14] It is in fact our interest in making a quantitative determination of the ectiveness of this response both to wave-length and to intensity in all the ys in which the eye responds to its stimulus, that has led us to attempt help bring about means of rendering energy measurements feasible for work in psychological optics. Under this heading would come, for exple, the investigation of the selectiveness of the eye's achromatic response h to wave-length and to intensity with its wide application to photometry light specification; the selectiveness of the chromatic response; the ctiveness to wave-length and intensity shown in the rise and decay of h types of response; the selectiveness found in after-image and contrast onse; etc. In fact neither the characteristics and possibilities of the eye a measuring instrument nor its peculiarities as a sense organ can be defily known without a common unit in terms of which to evaluate the difent wave-lengths to which it gives response. It is, moreover, obvious neither the unit nor method of measurement must in any way involve peculiarities of the responses of the eye itself.

this work our point of view is to investigate the responses of the eye as the physicist investigates the responses of his instruments. Too frentlY this investigation has received its direction from theories and docal conceptions. Such investigations can not help but be narrow in their e and are moreover apt to lead to wrong conclusions. Much more will ccomplished, we believe, by holding theoretical and doctrinal interests in ance for a time and to approach the study of the eye's responses with broader purpose of finding out what they are from the purely descrip- point of view, using methods and technique designed for such a purpose not for the confirmation or destruction of a theory. In any event the points of view should be kept separate in the work of investigation, and ie evaluation of results it should be clearly recognized to what degree a lt is the product of the method of working employed.

mated from 0.014 to 0.541 sec. And (c) it possesses great ad-vantages in the ease and convenience with which it may be used Its disadvantages are very similar to those of the photo-electri and selenium cells. (a) Like both of these instruments it i very selective in its response to wave-length and can not be used therefore, as an energy comparator of lights differing in spectro-radiometric composition without elaborate calibration. (b) Lik the selenium cell and photographic plate it is selective also in it response to intensity. It is perhaps more selective in this regar than the selenium cell. And (c) it responds only to the visibl spectrum and can, therefore, be calibrated against a black bod only with exceeding difficulty and with many chances of erro both in the calibration and its subsequent use. (See preface pp. vi-vii. If calibrated, the thermopile or some other instrumen which is sensitive to the total of radiation would ordinarily b employed and the calibration be made in terms of its response The work of calibration presents, moreover, great difficulties i case of the eye because of the lack of a fixed or closely repro-ducible scale of responses capable of numerical rating which ca be correlated with the responses of the calibrating instrumen Two possibilities for calibrating suggest themselves: (a) th determination of sensitivity curves, valid only for the particula eye, the exact physical and physiological conditions, etc. fo which the calibration was made, and for ranges of intensity i which no changes in relative sensitivity occur; and (b) the co relation of a just noticeable difference series with the correspon ing energy values for such parts of the spectrum as are mo frequently used. Neither of these possibilities, it is obviou would be of much service for any very wide use of the eye as measuring instrument. It will be the work of later papers t show in detail the selectiveness of the eye's response to wav length and to intensity.

III. A Convenient and Sensitive Radiometric Apparat for Work in Psychological and Physiological Optics.

The radiometric apparatus which we have used in our wo for the past four years consists of two thermopiles, a ve

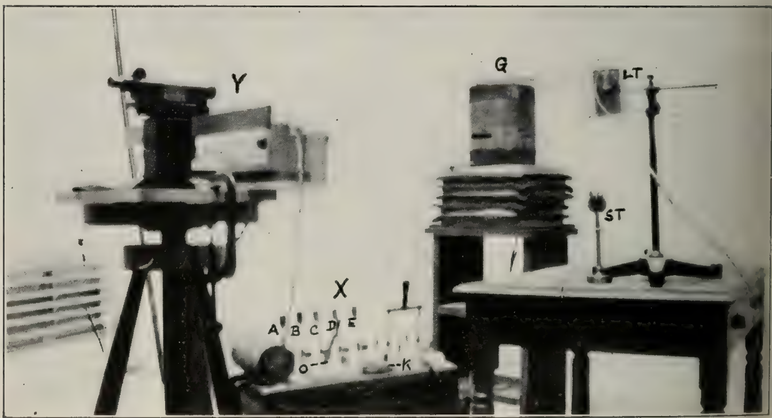


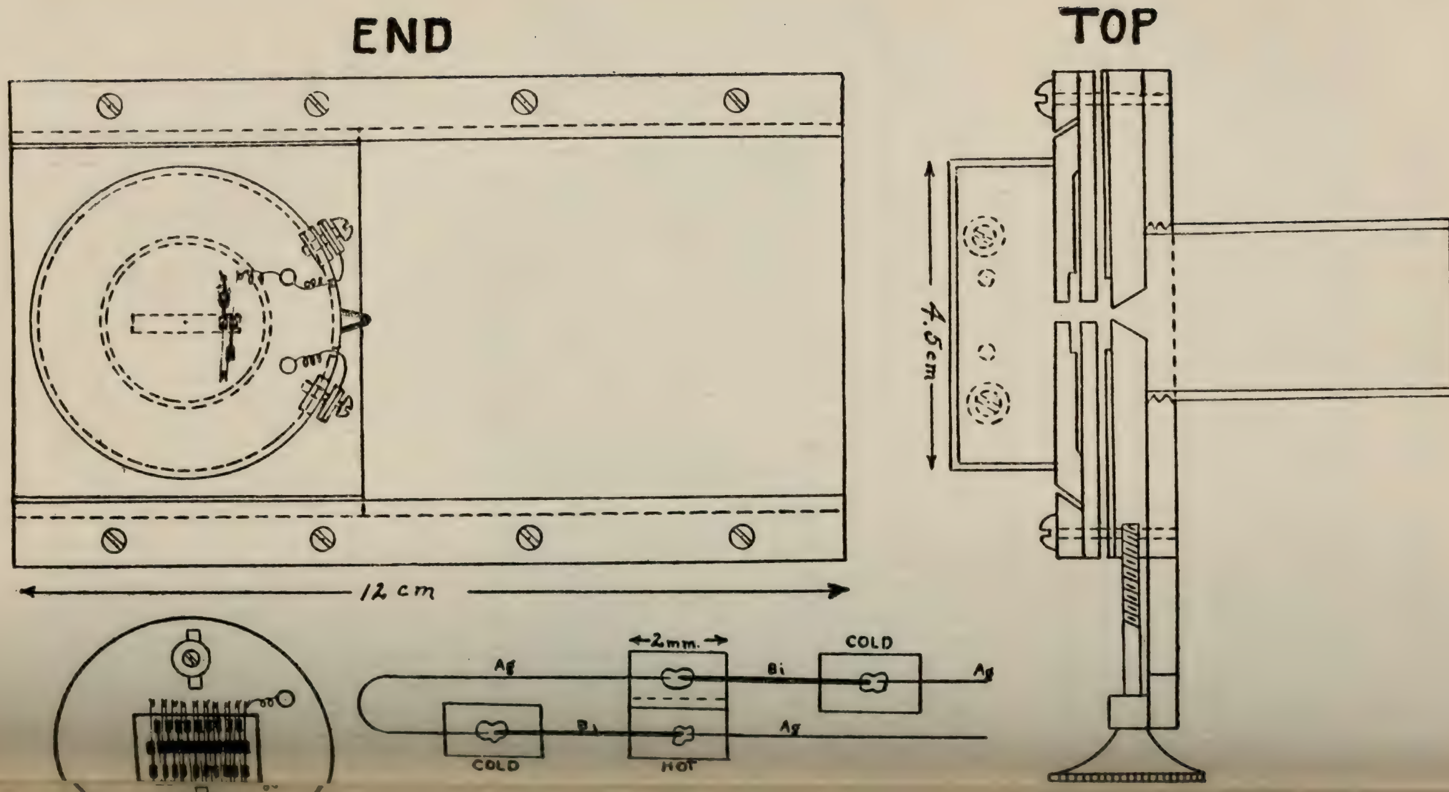
Fig. II

ensitive Thomson galvanometer and auxiliary apparatus for both hermopile and galvanometer. The two types of thermopile, the ;alvanometer, and the auxiliary apparatus for the thermopiles nd galvanometer were constructed by Dr. W. W. Coblentz of the Radiometric Division of the Bureau of Standards. This appartus is shown in Fig. II. LT is the linear thermopile in its brass nounting; ST is the surface thermopile; G is the galvanometer vith its magnetic shields; X is the auxiliary apparatus for hermopile and galvanometer; and Y is the telescope and scale.

A. THE LINEAR THERMOPILE

We are at present using two types of thermopile, a surface nd a linear pile. By using the two the energy of the light employed for the colored stimulus can be measured at three places: the opening of the campimeter screen with the surface pile hich has a receiving area just large enough to cover this openg; at the analyzing slit of the spectroscope with the linear pile; nd at the eye also with the linear pile. The linear pile with a reiving surface of 2 x 12 mm. is broad enough to cover either e analyzing slit or the colored image of this slit in the plane ngent to the anterior surface of the eye. The linear pile mearing at the slit and at the eye would thus be adequate alone for r purpose. Some additional advantage is gained perhaps by ving two instruments to serve as a check on each other and by asuring at three places instead of two.

The thermo-elements in both piles are of bismuth and silver. ne linear pile consists of 20 elements joined in series. These ments are in the form of wire, the bismuth 0.1 mm. in meter and the silver 0.051 mm. in diameter. The total resistce of the pile is 8.4 ohms; the area of the receiving surface is x 12 mm. In Fig. III this thermopile is shown drawn to scale. the lower right hand corner is shown a front view of the pile. e row of junctions in the center are the "hot" junctions or se exposed to the radiations to be measured. The rows on ier side of this are the "cold" or unexposed junctions. Ditly above is shown in detail the formation of a pair of "hot" l "cold" junctions. A bead of silver is used in welding the


END
TOP
4.5cm
12 cm
2mm.
COLD
Ag
Bi
Ag
Bi
Ag
HOT
COLD

bismuth and silver wires together to form the junctions. Over each of the "hot" junctions is fastened a receiving surface of tin 2 mm. broad and long enough for the successive pieces to overlap. That the heat conducted to the "cold" junctions may rapidly radiate and thus maintain a temperature difference between the two junctions as large and as constant as possible, a surface of tin of appropriate size is fastened also over each of the "cold" junctions. In the diagram are also shown the top and end views of the pile mounted for use. The pile is mounted on a flat metal base which slides up and down in grooves constructed on the edges of the frame containing the analyzing slit for the spectroscope. When in use it is lowered so that the analyzing slit opens directly upon the face of the pile. During the color observation, when not in use, the pile is raised to the upper part of the frame clear of the slit, and is fastened by means of a small hook which engages the upper edge of the frame.

B. THE SURFACE THERMOPILE

This thermopile was designed especially for our work by Dr. Coblentz. The object was to get a thermopile that would measure directly all of the light that fell on the opening of the ampimeter screen. This opening is 15 mm. in diameter. The urface of the thermopile was made 17 x 17 mm. The surace exposed to radiation was reduced to coincide with the stimuus-opening by means of a circular diaphragm 15 mm. in diamter. In order to shield the exposed junctions from the influence f air currents this aperture was covered with a thin sheet of lear glass (cover glass).

The pile consists of three units joined in parallel. Each unit onsists of 20 elements, bismuth and silver wire, joined in series. he bismuth wire is 0.1 mm. and the silver wire is 0.051 mm. in iameter. The total internal resistance of the pile is 3.65 ohms. ach of the "hot" junctions is covered with a surface of tin, x 1 x 0.02 mm. The "cold" junctions are to the rear of the hot" junctions instead of on either side as is the case in the near pile. That is, on leaving the "hot" junction, instead of inning to either side each of the elements is bent backward. To

simplify the construction, the radiating surfaces of tin which cover the "cold" junctions in the linear pile were omitted from the surface pile.

A diagram of the surface pile is shown in Fig. IV. A shows the mounting for the ivory supports to which the sensitive elements are attached; B shows the way in which the wires are bent from the "hot" junctions to form the "cold" junctions; C gives

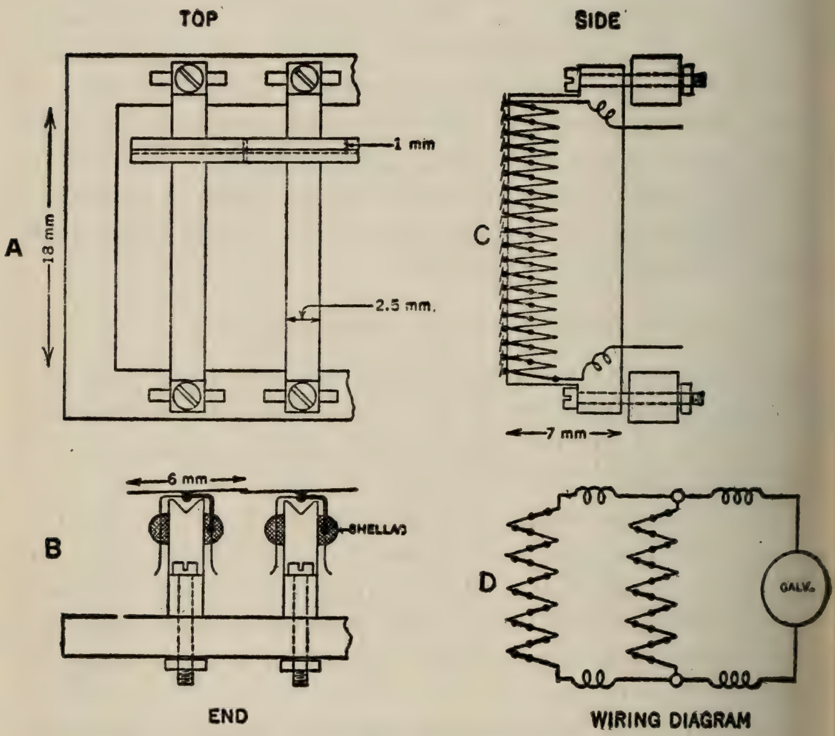
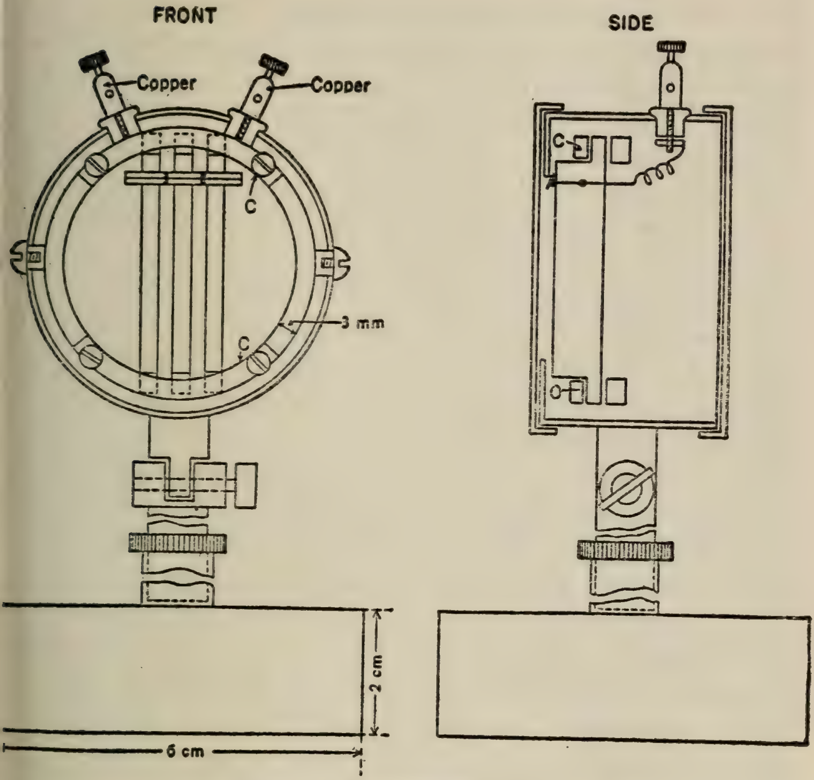


FIG. IV

a side view of one unit of the pile consisting of 20 thermo-elements mounted on the ivory support; and D shows the way in which the units are connected. In order to reduce the resistance and thus increase the sensitivity of the pile they are joined in parallel. In Fig. V are shown the front and side view of the holder for the thermopile.



HOLDER FOR THERMOPILE

FIG. V

In common with all surface radiometers of high sensitivity this urface thermopile causes some drift of the zero of the galva-iometer unless the instrument and the shutter enclosing it are arefully protected from changes in temperature due to contact vith the air of the room. Winding the terminals and body of the iermopile with cotton batting has overcome this effect almost ntirely.

C. THE RADIATION STANDARD

The thermopile might be used for equalizing energies or re-roducing given light intensities without calibration. However, its responses are to be converted into C. G. S. units, calibration

is necessary. For this a radiation standard is required. For this standard we employ a thoroughly seasoned carbon lamp the radiations from which have been carefully evaluated in terms of the primary standard conserved at the Bureau of Standards.[1] From the known radiations of this lamp the sensitivity of the pile per unit area is determined. This is done as follows. First the value of the radiations from the standard incident upon unit area must be computed. This computation is based ultimately upon the Stefan constant of total radiation from a black body: $T = 5.7 \times 10^{-12}$ watt per sq. cm. For our standard operated at 102.1 volts giving 0.4 ampere of current, the value of the radiation at a distance of 2 meters is 90.70×10^{-8} watt per sq. mm. With this radiation value known, the calibration of the thermopile becomes easy. It is set up at a distance of 2 meters from the radiation standard, and the deflections of the galvanometer, the sensitivity of which must have been determined just previous to the calibration, is obtained. From this value and the total amount of energy falling upon the surface of the pile, the amount of energy required to give a galvanometer deflection of 1 mm. is determined. This may be taken as a measure of the sensitivity of the radiometric apparatus. The total amount of energy falling on the pile is obtained by multiplying the radiation per sq. mm. at 2 m. by the area of the receiving surface of the pile and correcting this value for the absorption of the glass cover (12% in case of our instrument).

Since the galvanometer sensitivity may vary from time to time, it is necessary to establish for it a standard of sensitivity and to reckon the radiation sensitivity of the apparatus in terms of the reading at this standard sensitivity. In order to use the value so established in future work with the apparatus, it is necessary to determine each time the current sensitivity of the galvanometer which is quickly done with an especially devised testing apparatus, and to compute from this and the standard sensitivity a correction factor which has to be applied to all readings taken at this time.

[1] Coblentz, W. W. Bull. Bur. Standards, 1914, 11, p. 87.

D. THE GALVANOMETER

The galvanometer used was constructed specially for the thermopile employed. It is of the Paschen small-coil type, shielded from magnetic influence by four cylindrical soft iron shields. Its parts are as follows. The magnetic field of the instrument is given by four coils each having a resistance of 6 ohms. Each coil is wound in three layers, 2 ohms per layer. The wire used was B & S gauge Nos. 38, 30, and 26, single covered silk insulation, the diameter of the bare wires being respectively 0.101, 0.255, 0.405 mm., and the lengths 92, 595, and 1375 cm. Each coil has a diameter of 2.8 cm. and a thickness of 7 mm. The coils are joined in pairs, series parallel, giving a total resistance of 6.58 ohms. The needle system consists of two groups of six magnets placed above and below the mirror. The magnets are of tungsten steel and are from 1.5 to 2.5 mm. in length; from 0.3-0.4 mm. in width; and 0.1 mm. in thickness. They are mounted so that each group of magnets has the form of an ellipse. The mirror is of thin cover glass 2 mm. x 3 mm., platinized by cathode discharge. The magnet groups and the mirror are mounted on a segment of a very small glass rod in such a way that the centers of the groups are 33.5 mm. apart and the mirror is midway between them. At the lower end of the rod is attached a damping vane of bolometer platinum 5 x 4 x 0.003 mm. The needle system weighing 12-15 mg. was made heavy to minimize the influence of earth tremors. It is suspended between the coils by means of an extremely fine quartz fiber.

The assembled galvanometer consisting of base provided with leveling screws, the coils and their ebonite supports, the needle system and the containing tube for its suspension, is drawn to scale in Fig. VI and needs little explanation. The coils, coated with paraffine to give the insulation needed, are attached to the ebonite supports by means of soft wax (a mixture of Venice turpentine and beeswax which hardens to the desired consistency on standing). Soft wax is used because it permits of an easy and convenient adjustment of the position of the coils, the faces of which should be brought to exact parallelism. This can

be done very conveniently by moving up and down between the faces of the coils a rectangular object of the proper width, *e.g.*, a microscope section glass. Having been rendered parallel the faces of the coil are brought into the vertical by means of the leveling screws on the base of the instrument. The quartz fiber which suspends the needle system passes through the containing tube and is attached at the top to a short brass pin with a milled head, held in place by means of a set screw. The needle system is fastened to the quartz fiber with shellac. The attachment of the needle system to the quartz fiber and this in turn to the brass pin is made on a special mounting board designed for the purpose. The housing of the galvanometer is of microscope section glass. This not only prevents disturbances of the needle system due to air currents but permits of an excellent illumination of the interior of the galvanometer.

The magnetic shielding[215] of the galvanometer consists of an inner laminated cylinder made up of six layers of transformer iron, 3½ inches in diameter, and three sections of soft iron pipe 5, 6 and 10 inches in diameter respectively, and 10 inches high. Each of these shields contains a horizontal window 1 cm. high and 8 cm. long through which the mirror is viewed. They rest on a slab of slate and a glass plate is put on top. Care is taken to keep the shields well annealed, but in spite of this some magnetism is acquired in handling. The influence of this and of the earth's field on the needle system has to be overcome if the galvanometer is to have the long period needed for a high current sensitivity. This might be done in two ways. (1) The unknown and very complex field due to the iron shields could be ascertained by means of control magnets; or (2) a stronger and simpler known field could be created and this field be weakened to the desired amount. The latter is found to be the more feasible procedure. The field is created by a short magnet placed under the base of the galvanometer in such a position that the mirror and its reflected

[215] For working in localities close to street cars and other magnetic disturbances, it is necessary to use a more thoroughly shielded galvanometer, the coils of which are imbedded in soft iron. See Bull. Bur. Standards, 1916, *13*, p. 423.

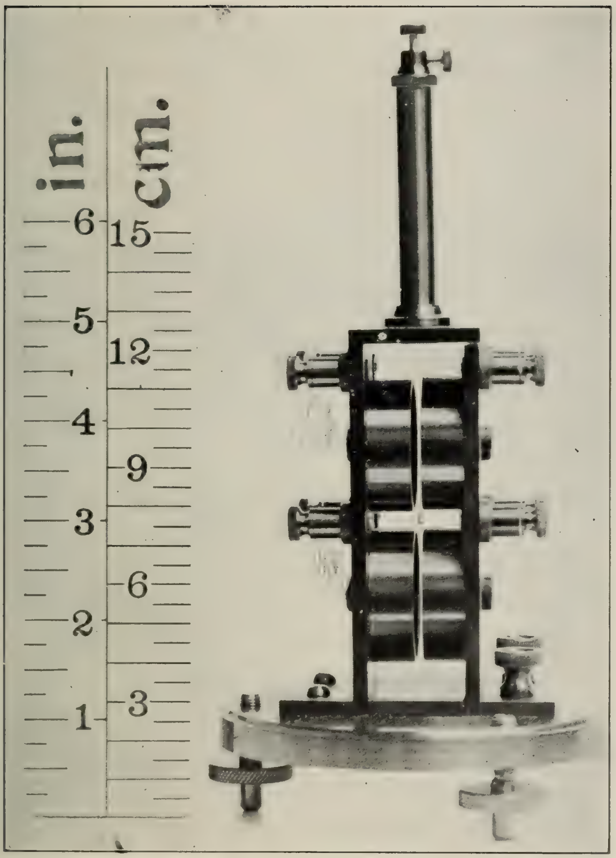


Fig. VI

scale are brought into the field of the observing telescope. This field is then weakened the desired amount by a larger magnet of greater strength placed on the glass plate covering the top of the shields. The large magnet is rotated about the vertical axis of the galvanometer until the needle which follows it passes quickly through a neutral point and rotates in the opposite direction. In this position of the magnets the effective field is not so great as the moment of torsion of the needle system, and the galvanometer should have a long period and a high current sensitivity.

E. THE AUXILIARY APPARATUS

This consists of a device for testing the sensitivity of the galvanometer, a set of resistance coils to cut down the throw of current from the thermopile, and a reading telescope and scale.

1. *The sensitivity tester for the galvanometer.* The sensitivity tester consists of a dry battery giving an E.M.F. of 1.43 volts, and of three shunt coils with the necessary switches mounted on a suitable base. The shunt coils have a resistance of 1000, 100 and 1000 ohms respectively and are designed to pass 1.43×10^{-8} ampere of current through the galvanometer. This divided by the number of scale divisions of the deflections produced gives the value of the current required to give a deflection of one scale division, or the sensitivity of the instrument. That is, the formula expressing the sensitivity is $i = \frac{1.43 \times 10^{-8}}{d}$, in which d is the number of scale divisions in the deflection; 1.43×10^{-8} is the total strength of the current; and i is the amount of current required to produce a unit deflection. For example, the galvanometer we use when adjusted to a 3 second period single swing gives a deflection of 40 scale divisions. This gives a sensitivity of $\frac{1.43 \times 10^{-8}}{40}$, or $.575 \times 10^{-10}$.

The galvanometer may be connected either with the sensitivity tester or the thermopile by means of two-pole, double-throw knife switch, as is shown at x in Figure II. When connected with the shunt coils of the sensitivity tester, the circuit is closed with the

dry cell by means of a key shown at k. Sometimes when the galvanometer is adjusted to a high degree of sensitivity a big shift of the zero occurs when the double-throw switch is changed from the pole connecting the galvanometer with the sensitivity tester to the pole connecting it with the thermopile. This makes it necessary to readjust the magnets above the galvanometer to bring the zero again to the center of the scale. To avoid this a further means is provided for testing the sensitivity of the galvanometer without opening the switch which connects the thermopile with the galvanometer. This consists of an auxiliary coil of wire which is connected directly with the dry battery and a key to close the circuit, shown at o. This coil is mounted in a fixed position on the casing about the tube containing the suspension above the needle system. When a current is sent through the coil a deflection is given which is proportional to the current sensitivity of the galvanometer and in fixed ratio to the deflection that is produced when the same amount of current is sent through the shunt coils of the sensitivity tester to the galvanometer coils. This fixed ratio may be determined once and for all by closing each of these two circuits in turn with the dry cell and comparing the deflections produced.

2. *Special resistance coils.* The resistance coils designed to cut down the throw of current from the thermopile to the galvanometer are thrown into the thermopile circuit by means of a series of single-pole, single-throw knife switches shown at A, B, C, D, and E, Fig. I. When A is closed no resistance is added, the full current passes to the galvanometer, and the true deflection is produced. When, however, B, C, D, and E are closed, the current is made to pass through 10, 40, 100, and 191 ohms respectively, and the observed deflections must be multiplied by the following factors to give the true deflections: B=1.657; C=3.63; D=7.57; and E=13.55.

3. *The telescope and scale.* The telescope and scale used are of the kind ordinarily employed when precision is wanted in the reading of a sensitive galvanometer. The scale is graduated to millimeters and illuminated by two 40-watt tungsten lamps which can be moved along in front of the scale to give the maximum

illumination of the part of the scale reflected by the mirror. The telescope is fitted with a lens system that will permit the clear reading of the scale at a distance of 2 meters. At this distance the definition is such that the scale can be read to 0.5 mm.

We recommend to workers in psychological optics the apparatus described in the foregoing pages as feasible, adequately sensitive, and precise. We feel that especial acknowledgment is due to Dr. Coblentz for a notable contribution to the apparatus available for the more definitely quantitative work in the subject.

'HE SELECTIVENESS OF THE ACHROMATIC RESPONSE OF THE EYE TO WAVE-LENGTH AND ITS CHANGE WITH CHANGE OF INTENSITY OF LIGHT

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In a previous paper, "Radiometric Apparatus for Use in ychological and Physiological Optics—Including a Discuson of the Various Types of Instruments that have been used r Measuring Light Intensities," *Psychological Review Monraphs,* XXIII (5), 1917, we have pointed out that the selenm cell, the photographic plate, the eye and the photo-electric l are all selective in their response to wave-length and that in se of the first three the amount of this selectiveness varies th the intensity of the light used.[1] It was also stated that e of the purposes to which the apparatus described in that per is to be devoted, is a study of the selectiveness of the e's responses to wave-length and to intensity. Bearing on s point we need scarcely repeat that the kind and amount selectiveness shown by the eye in its responses can be ermined only by comparing it with an instrument whose ponses are non-selective or directly proportional to the ergy or physical value of the light waves employed. The itrument we have selected and described as most feasible this purpose in the present stage of development of radiotric apparatus is the thermopile.[2]

Jsing the responses of the thermopile, therefore, as a

[1] With regard to whether or not the selectiveness of response of the to-electric cell changes with the intensity of the incident light, inigators disagree. In the article referred to above will be found a umé of the literature on this point.

[2] For a similar investigation by means of the thermopile of the selecless of action of the selenium cell, see A. H. Pfund, *Philosophical azine,* vii., (6) 1904, p. 26; see also Brown and Sieg, *Physical Re-*, iv., 1914, p. 48.

is obvious that the deviations from proportionality to the energy

standard of reference we have undertaken a somewhat ex- tensive investigation of the selectiveness of both the achro matic and chromatic responses of the eye to wave-length Preliminary to the detailed report of this investigation whicl cannot be made for some time, it may not be out of place t give here a few comparisons of the achromatic responses o the eye with those of the thermopile. These comparison were made four years ago and have been withheld from prin in the hope of a speedier completion of a larger part of th study. They have in general taken three forms: (a) a com parison at different intensities of the photometric value o stimuli made equal in energy value; (b) a similar compariso of stimuli having the relative energy values of a prismati spectrum of a given type; and (c) a comparison at differer intensities of the energy values of stimuli made equal photc metrically. This, it scarcely need be pointed out, is only pa of the programme that should be followed in making a stud of the peculiarities and characteristics of the achromatic re sponse to wave-length and in carrying out the intercheckin of methods that is needed for making such a study; but as y time has not been available to cover this broader field even i a preliminary way.

In this preliminary work time has been had for the use c only a limited number of stimuli and intensities. In lat work results will be given for a part of the work, at least, fc a greater number of points in the spectrum and for a great number and range of intensities of light. The lights used a stimuli were a red, orange, yellow, yellow-green, green, gree

of the light waves which are shown in the responses of the seleniu cell, the photoelectric cell and the photographic plate are in need investigation as well as those which are shown in the responses of t eye. Until these deviations are known quantitatively and corrected f in each individual apparatus, instruments of the type can not be us directly to measure energy. They may be used to advantage, perha as balancing or equating instruments, but then only when the lights e ployed are of the same composition; or again in cases where it is pc sible and feasible to determine and use correction factors. If the ligl are not of the same composition it is obvious that the selectiveness response of the instrument will make the balance a false one or one n proportional to the actual amounts of energy involved.

lue, blue, violet and a mixed or white light. The colored ghts unless otherwise specified were narrow bands taken om the following regions of the spectrum: 655$\mu\mu$, 616$\mu\mu$, 80$\mu\mu$, 553$\mu\mu$, 522$\mu\mu$, 488$\mu\mu$, 463$\mu\mu$, and 439$\mu\mu$. In order to et the high intensities needed at the photometer head, the nalyzing slit was purposely made somewhat wide,—0.5575 im. This width of slit was kept constant for all parts of the ectrum. If our problem had been such that smallness of inge of wave-length had been a more important condition ian intensity, a narrower slit would have been used. We ive not considered, however, that smallness of range of wave-ngth was as important a condition to secure for the purposes this investigation as the range of intensities that was made ssible by using the greater width of slit. The white light as obtained by synthesizing the spectrum between wave-igths 730 and 432$\mu\mu$. The above lights were used in mak-g this comparison in part because of the importance to cur-nt work in heterochromatic photometry of a comparative iowledge of the eye's peculiarities of response to these hts; and in part because they are taken from those parts the spectrum to which the eye shows its most significant anges in selectiveness of response with changes of light ensity. The lights, both colored and white, were taken om the spectrum (a) in order that the former should be as mogeneous as to wave-length as was practicable; and (b) order that both should be free from the infra-red and ultra-let radiations which would affect the thermopile but not eye. In synthesizing the white light from the spectrum e was taken, therefore, to use only wave-lengths safely hin the red at one end and the violet at the other.[2a] The it was examined in every case at the analyzing slit for im-ities by means of a small Hilger direct vision spectroscope vided with an illuminated scale. When found, impurities e absorbed out by thin gelatines selected so as to cut out little of the useful light as possible. These gelatines were ced over the analyzing slit and were held in position by rt clips fastened to the front surface of the jaws, the edges which formed the slit. The importance of securing a high

The work with the white light will be given in a later paper.

degree of purity when correlations are to be made between the responses of the eye for a given region of the spectrum and energy values is obvious, *i. e.*, in proportion to their energy the alien wave-lengths would affect the eye differently from the wave-lengths under investigation.[3]

In making this comparison between the relative photometric and radiometric values for the different wave-lengths for the first type of investigation mentioned above, it was desirable that the same amount and as nearly as possible the same radiation density of light should fall on the receiving surface of both instruments. This was accomplished by making both determinations at the same place and having the same cross section of the collimated beam of light fall on the receiving surface of the two instruments. In detail the procedure was as follows: The colored light was obtained by means of the spectroscopic apparatus described in a previous paper.[4] To prevent an undue reduction by spreading and to make possible the requirements mentioned above with regard to the incidence of equal amounts and densities of light on the receiving surfaces of the two instruments, the waves of light emerging from the analyzing slit of this apparatus were rendered approximately parallel by being passed through a collimating lens placed at a distance from the slit equal to its focal length. At a given place in the beam were mounted interchangeably the thermopile and the photometer head.[5] The thermopile was of the surface type[6] with a receiving area of 15 x 15 mm.

[3] In their work on the determination of the visibility of radiation in the red end of the visible spectrum, Hyde and Forsythe (*Astrophysical Journal*, xliv, 1915, p. 289) found impurities to the value of about 20 per cent. at $\lambda = 0.76\mu$. In our own work determinations made with and without precautions for absorbing the scattered light show differences in result which are great enough to be considered of significance. In the work of Nutting and of Ives on the visibility of radiation, nothing is said about stray light or about precautions for eliminating it or correcting for it.

[4] C. E. Ferree and G. Rand. A Spectroscopic Apparatus for the Investigation of the Color Sensitivity of the Retina, Central and Peripheral. *Journal of Experimental Psychology*, I., 1916, pp. 247-283.

[5] Owing to the smaller amount of energies represented in the shorte

[6] C. E. Ferree and G. Rand. Radiometric Apparatus for Use in Psychological and Physiological Optics. *Psychological Review Monographs*, xxiv., 1917.

The photometer head consisted of a 60° brass prism (a modified form of the type of photometer head known as the Ritchie wedge) of such dimensions that the two surfaces adjacent to the 60° angle were each equal in area to the receiving surface of the thermopile. These two surfaces were covered with magnesium oxide deposited from the burning metal. They received the standard and comparison lights and served as fields for the photometric comparison. In order that the same cross section of light should fall on the photometric surface as fell on the receiving surface of the thermopile, the arrangement of the apparatus was such that the photometer surface was normal to the beam of light. This relation of axis of beam of light to photometer surface was made to apply alike both to the standard and comparison lights. To compensate for possible inequalities in the coefficients of reflection of the two surfaces the two faces could be interchanged by rotating the prism 180° about its horizontal axis. In making the photometric determination the colored light was balanced against the light from a standardized lamp. The standard used was a single loop street series tungsten seasoned and standardized by the New York Electrical Testing Laboratories to operate at 10.7 candle-power. Further to secure constancy of light flux this lamp was operated by storage batteries. In making the photometric-radiometric comparison the colored lights were, as stated above, first made radiometrically equal to the violet at the point of work. The thermopile was then removed, the photometer head put in its place,

wave-lengths, for example, in the blue and violet, it was a matter of some difficulty to make an energy measurement of these wave-lengths with satisfactory degree of precision at the position of the photometer head. It was thought better, therefore, to determine a reduction factor representing the relation of the total amount of energy emerging from the slit and the amount that was contained in the cross section falling on the photometer head. This was done, for example, by measuring the red at the slit with the linear pile and again at the photometer head with the surface pile, the latter receiving precisely the same cross section as fell on the photometer head. This factor having been determined, the light was measured at the slit with the linear pile and the factor was applied to give the energy value of the cross section incident on the photometer head.

and the lights incident on the two surfaces of the prism brought to a photometric balance by adjusting the position of the standard lamp.

Since the procedure is somewhat unfamiliar to psychologists, it may not be out of place to give here a brief description of how energy measurements are made by means of a thermopile. A description of the procedure at one of the places at which measurements were made, namely, the analyzing slit will be sufficient to show in a general way the method we have used in making these measurements. The thermopile to be used is placed in position immediately behind the slit and a blackened aluminum shutter is interposed in the path of the beam of light between the slit and the end of the objective tube of the spectroscope. Preliminary to the exposure of the thermopile to the light to be measured, the current sensitivity of the galvanometer is tested by means of a special device provided for this purpose in the construction of the galvanometer.[7] With regard to this procedure it need scarcely be pointed out that the current sensitivity of the galvanometer varies with the period or time of the single swing of its needle system. Since it is not possible to control the field so as to get this period always the same, it is necessary, if results are to be compared, to take some sensitivity as standard and to convert all readings into deflections for the standard sensitivity by means of a correction factor determined at each setting. For a detailed description of the method of determining this factor, see *Psychological Review Monographs,* XXIV, 1917.

The thermopile is next connected with the galvanometer and the light allowed to fall on its receiving surface until a temperature equilibrium is reached (*ca.* three seconds for our thermopile). The deflections are read by means of the telescope and scale and the readings are corrected to standard sensitivity by means of the factor previously determined. The final step in the process of measuring is the calibration of the apparatus,

[7] This device consists of a special galvanometer coil, dry battery circuit and switch board with finely graduated resistance. For a description of this device, see *Psychological Review Monographs,* xxiv., 1917.

i. e., the value of 1 mm. of deflection in radiometric units is determined for the area of thermopile exposed. To do this a radiation standard, the value of the radiations from which is already known, has to be employed. The standard used by us is a carbon lamp especially seasoned and prepared for the purpose by W. W. Coblentz[8] of the radiometric division of the Bureau of Standards. This lamp is placed on a photometer bar 2 meters from the thermopile and operated at one of the intensities for which the calibration was made, in our case 0.40 ampere. The thermopile is exposed to its radiations with the same area of receiving surface as was used in case of the lights measured, and the galvanometer deflection is recorded. From the deflections obtained the value of 1 mm. of deflection, or the radiation sensitivity of the apparatus under the conditions given, is computed from the known amount of energy falling on the surface of the thermopile. Having the factor expressing the radiation sensitivity of the apparatus, the deflections produced by the wave-lengths of light measured are readily converted into energy units. The radiation sensitivity of the linear thermopile used by us was computed in a given case, for example, from the following data. The energy value of the radiations per sq. mm. at a distance of 2 m. from the standard lamp operated by 0.40 amperes is 90.70×10^{-8} watts. The deflections of the galvanometer corrected to a sensitivity of $i = 1 \times 10^{-10}$ ampere produced by this intensity of radiation falling on the same area of receiving surface as was used in measuring the lights employed as stimuli, and corrected for the absorption of the glass cover of the thermopile, was 625.625 mm. The area of surface exposed was 6.862 sq. mm., and the time of exposure was 3 sec. The sensitivity of the instrument per sq. mm. of receiving surface was, therefore, 145×10^{-11} watts. By means of this factor the galvanometer readings produced by the different wave-lengths of light may be readily converted into the energy value of light falling on the receiving surface of the thermopile.

However, as previously stated, the comparisons treated of

[8] W. W. Coblentz. Measurements on Standards of Radiation in Absolute Value. *Bulletin Bureau of Standards*, xi., 1914, pp. 87-100.

in this paper were made four years ago. At that time we were not provided with a radiation standard for the calibration of our apparatus. Without this calibration, the stimuli employed could be equalized in energy or their energy values could be compared from the galvanometer deflections produced, but the amounts of energy used could not be expressed in the conventional units. If an expression of the intensity of the stimuli were to be made in energy units, all the work done at that time would have had to be repeated. There has not been time to do this in season for the present paper. All of the radiometric values needed for the comparisons made in this paper will be given, therefore, in terms of relative galvanometer deflections converted for convenience of representation into an arbitrary scale in which the largest deflection is given the value of 100. This scale has been constructed separately for each table in which relative energy values are represented.

TABLE I

Showing the change in the relative selectiveness of the achromatic response of the eye to wave-length produced by varying the intensity of the light. In this table is given the photometric value in meter-candles of wave-lengths selected from different parts of equal energy spectra sustaining to each other the following ratios of intensity: A, 1/2 A, 1/4 A and 1/12 A.

Stimulus	Photometric value of stimulus in meter-candles			
	Intensity A	Intensity 1/2 A	Intensity 1/4 A	Intensity 1/12
Red (655 $\mu\mu$)	0.98	0.47	0.15	0.015
Orange (616 $\mu\mu$)	1.345	0.66	0.35	0.103
Yellow (580 $\mu\mu$)	3.4	1.5	0.825	0.35
Yellow-green (553 $\mu\mu$)	4.02	1.92	0.96	0.777
Green (522 $\mu\mu$)	2.44	1.34	0.82	0.56
Green-blue (488 $\mu\mu$)	1.42	1.06	0.79	0.523
Blue (463 $\mu\mu$)	0.817	0.546	0.28	0.25
Violet (439 $\mu\mu$)	0.56	0.26	0.164	0.128

The results for the first type of comparison are given in Tables I and II and Chart I. In Table I, Column 2, are given the photometric values of stimuli used in making the investigation, all made equal in energy value to the violet ($439\mu\mu$), width of analyzing slit 0.5575 mm., corrected for impurities, in a prismatic (CS_2) spectrum given by a Nernst filament operated by 0.6 ampere of current. This will be called Intensity A. In Columns 3, 4 and 5 are given the results of a comparison of the photometric values of these same groups of wave-lengths made equal in energy at three lower intensities: 1/2 A, 1/4 A and 1/12 A.

Spectra 1/2 A, 1/4 A and 1/12 A were obtained from A by the use of the sectored disc with a proper ratio of open to

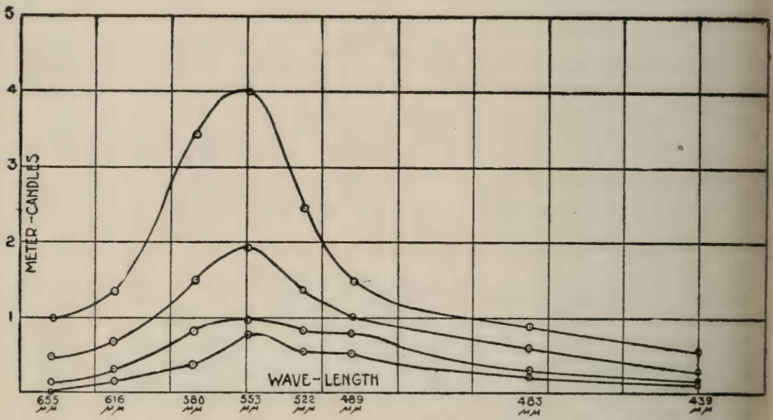
TABLE II

Showing the change in the selectiveness of the achromatic response of the eye to wave-length produced by varying the intensity of light. In this table are shown in per cent of the original value the photometric values of each of the colored lights when their energy values have been reduced respectively to 1/2, 1/4, and 1/12 of the values present in equal energy Spectrum A. The changes in the deviations of the relative photometric from the relative radiometric values produced by the changes of intensity may be noted by comparing the percentages in Column 2 with 50 per cent; in Column 3 with 25 per cent; and in Column 4 with 8.33 per cent.

Stimulus	Relation of photometric value of 1/2 A to A expressed in per cent	Relation of photometric value of 1/4 A to A expressed in per cent	Relation of photometric value of 1/12 A to A expressed in per cent
Red............ ($655\ \mu\mu$)	47.96	15.31	1.53
Orange......... ($616\ \mu\mu$)	49.07	26.02	7.66
Yellow .... ($580\ \mu\mu$)	44.12	24.26	10.29
Yellow-green.... ($533\ \mu\mu$)	47.76	23.88	19.33
Green.......... ($522\ \mu\mu$)	54.92	33.61	22.95
Green-blue...... ($488\ \mu\mu$)	74.65	55.63	36.83
Blue............ ($463\ \mu\mu$)	66.83	34.27	30.60
Violet.......... ($439\ \mu\mu$)	46.43	29.29	22.86

CHART I

Showing the change in the relative selectiveness of the achromatic response of the eye to wave-length produced by varying the intensity of the light. In this chart is represented the photometric value in meter-candles of wave-lengths selected from eight different parts of equal energy spectra sustaining to each other the following ratios of intensity: A, ½ A, ¼ A, and 1/12 A.



closed sector inserted between the collimator lens and the prism of the spectroscope. The photometric-radiometric comparison was made with the apparatus and by the method already described. A graphic representation of these results is given in Chart I.

In order to show the changes in the selectiveness of the achromatic response to wave-length produced by changing the intensity of light, Table II has been prepared. In the several columns of this table are shown in per cent. of the original value the photometric values of each of the colored lights when their energy values have been reduced respectively to 1/2, 1/4 and 1/12 of the values present in Spectrum A. Since A is an equal energy spectrum, the reduced spectra are also equal energy spectra. The changes in the deviations of the relative photometric from the relative radiometric values produced by the changes of intensity will be noted by comparing the percentages in column 2 with 50 per cent.; in column 3 with 25 per cent.; and in column 4 with 8.33 per cent. In this table a high value of the percentage

expressing the relation of the photometric values of A, 1/2 A, 1/4 A and 1/12 A indicates a relatively slow change in photometric value for a given change of intensity; and a low per cent. value indicates a relatively rapid change. Column 2 shows that when the equal energy spectrum A is reduced one-half in intensity, green ($\lambda 522 \mu\mu$), green-blue ($\lambda 488 \mu\mu$) and blue ($\lambda 463 \mu\mu$) darken relatively slowly; and yellow ($\lambda 580 \mu\mu$) the most rapidly. Columns 3 and 4 show that for reductions to one-fourth and one-twelfth, the slowest rate of darkening is still from $522 \mu\mu$-$463 \mu\mu$; the most rapid rate, however, has shifted to the red ($\lambda 655 \mu\mu$).

The results of the second type of comparison are given in Tables III and IV and in Chart II. In Table III are given the results of a comparison of the photometric values of the wave-lengths used in the preceding determinations from spec-

TABLE III

Showing the change in the achromatic response of the eye to wave-length produced by varying the intensity of light. In this table is given the photometric value in meter-candles of wave-lengths selected from different parts of prismatic spectra not equalized in energy, sustaining to each other the following ratios of intensity: A, 1/2 A, 1/12 A, and 1/45 A. The source of light was a Nernst filament operated by 0.6 ampere of current.

Stimulus	Photometric value of stimuli in meter-candles				Relative energy value of stimulus for Intensity A at photometer head
	Intensity A	Intensity 1/2 A	Intensity 1/12 A	Intensity 1/45 A	
Red...... (655 $\mu\mu$)	2.86	1.18	0.405	0.128	100.00
Orange.... (616 $\mu\mu$)	6.96	2.85	0.70	0.34	58.74
Yellow.... (580 $\mu\mu$)	7.74	3.34	0.92	0.458	30.36
Yellow-green (553 $\mu\mu$)	7.12	3.1	0.78	0.42	19.78
Green..... (522 $\mu\mu$)	5.50	2.76	0.55	0.30	13.59
Green-blue. (488 $\mu\mu$)	3.60	2.25	0.49	0.25	8.39
Blue...... (463 $\mu\mu$)	0.80	0.535	0.242	0.12	6.34
Violet..... (439 $\mu\mu$)	0.56	0.26	0.128	0.07	6.16

TABLE IV

Showing the change in the achromatic response of the eye to wave-length produced by varying the intensity of light. In this table are shown in per cent of the original value, the photometric values of each of the colored lights when their energy values have been reduced to 1/2, 1/12, and 1/45 of the values present in prismatic Spectrum A. The changes in the deviations of the relative photometric from the relative radiometric values produced by the change of intensity may be noted by comparing the percentages in Column 2 with 50 per cent; in Column 3 with 8.33 per cent; and in Column 4 with 2.22 per cent.

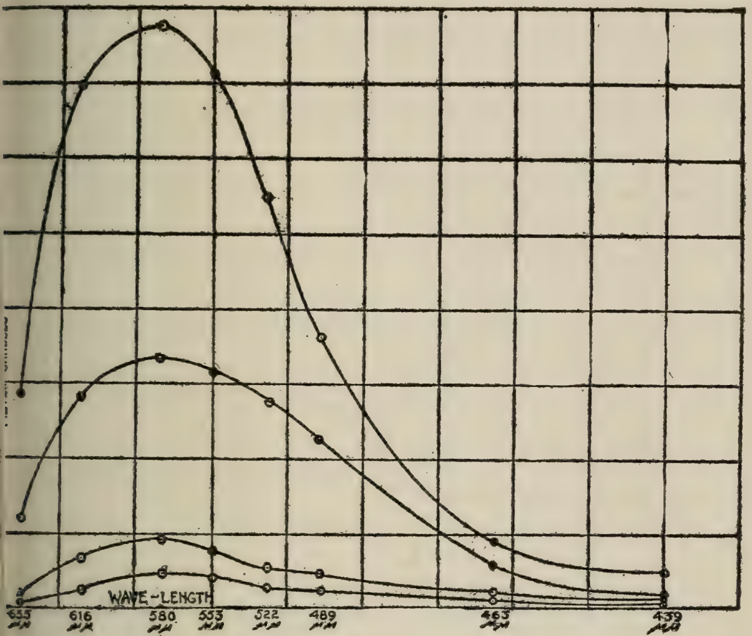
Stimulus	Relation of photometric value of 1/2 A to A expressed in per cent	Relation of photometric value of 1/12 A to A expressed in per cent	Relation of photometric value of 1/45 A to A expressed in per cent
Red (655 $\mu\mu$)	41.26	14.16	4.47
Orange (616 $\mu\mu$)	40.95	10.06	4.89
Yellow (580 $\mu\mu$)	43.15	11.89	5.92
Yellow-green (553 $\mu\mu$)	43.50	10.95	5.90
Green (522 $\mu\mu$)	50.20	10.00	5.50
Green-blue (488 $\mu\mu$)	62.50	13.61	6.94
Blue (463 $\mu\mu$)	66.88	30.25	15.00
Violet (439 $\mu\mu$)	46.43	22.86	12.50

tra of four intensities not equalized in energy: A, 1/2 A, 1/12 A, and 1/45 A. Intensity A is that given by the Nernst filament operated at 0.6 ampere of current. Intensities 1/2 A, 1/12 A, and 1/45 A were gotten by reducing Intensity A by means of a sectored disc. In making these comparisons there was, as is stated above, no attempt at an equalization of the energies of the lights employed. It was desired to find their relative photometric values at the four intensities with the type of distribution that occurs in such a spectrum as was used by us (prismatic CS_2 with gelatines interposed at the analyzing slit for the absorption of impurities) with the given width of analyzing slit.

This distribution is shown in Column 6, Table III and in Chart III.

CHART II

Showing the change in the achromatic response of the eye to wave-length produced by varying the intensity of light. In this chart is represented the photometric value in meter-candles of wave-lengths selected from nine different parts of prismatic spectra not equalized in energy, sustaining to each other the following ratios of intensity: A, ½ A, 1/12 A, and 1/45 A. The source of light was a Nernst filament operated by 0.6 ampere of current.

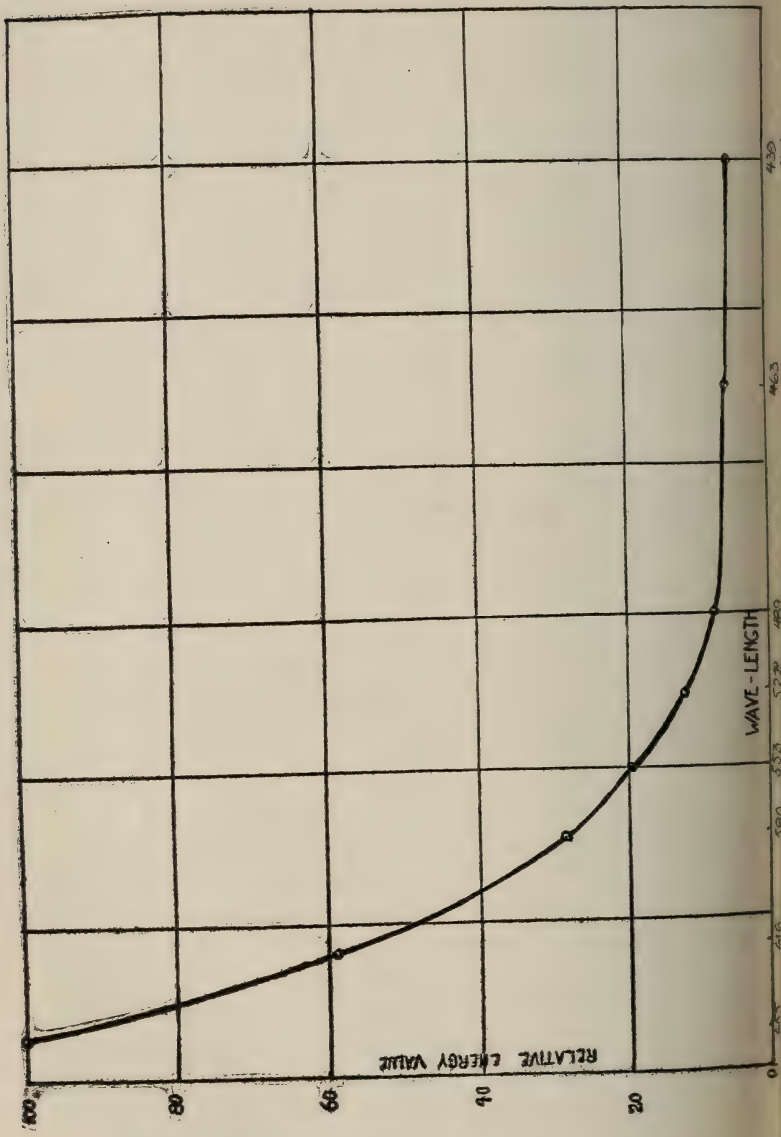


A graphic representation of the results of Table III is given ı Chart II. Supplementary to Chart II, Chart III has been repared. In this chart is given a graphic representation of the elative energy values of the colored lights used for Intensity A, ıat is, a graphic representation at eight points of the distribution of energy in the spectrum used by us when the width of ıe analyzing slit is equal to 0.5575 mm. This chart is contructed from the results in Column 6, Table III. In plotting ıe curve wave-lengths are represented along the abscissa and elative energy values along the ordinate.

Table IV has been prepared to make the same kind of

CHART III

Showing a graphic representation of the relative energy values of the colored lights used for Intensity A, Chart II and Tables III and IV.



showing of the results in Table III as was made in Table II for the determinations for the equal energy spectra. In this table are shown in per cent. of the original value the photometric values of each of the colored lights when their energy values have been reduced respectively to 1/2, 1/12, and 1/45 of their values at Intensity A. The changes in the deviations of the relative photometric from the relative radiometric values produced by the changes of intensity may be seen by comparing the percentages in Column 2 with 50 per cent.; in Column 3, with 8.33 per cent.; and in Column 4 with 2.22 per cent. In this table it is again seen that in general a rapid decrease of photometric value for a given decrease in energy is characteristic of the long wavelengths and a relatively slow decrease of the short wavelengths.

The foregoing results express relations between the photometric and radiometric values of the light waves employed at the given intensities. While this type of relation may be of nterest to the physicist and more particularly to the lighting specialist, it does not permit of a rating either of amounts of esponse, or of sensitivity or power of giving response in a vay which is, strictly speaking, quantitative. That is, in order hat the rating or comparison of sensitivities may be made uantitative, it must be possible from the data at hand to ompare numerically both the amounts of response and the mounts of stimulus used to give the response. In this conection it need scarcely be pointed out that the photometric alues plotted in the preceding curves cannot be considered s amounts of response or sensation quantities, or as sustaing any simple relation to amounts of response. Two suraces, for example, illuminated respectively by four and one ieter-candles of light do not arouse sensations which sustain each other the ratio of four to one, nor have we any knowlIge of what ratio they do sustain to each other. That is, the iotometric units: the candle, the lumen, the meter-candle, the mbert, etc., are all physical (not sensation) magnitudes difring in kind essentially from the erg, the watt, etc., only in at in photometric practice their comparison with the standd is made by the eye, the responses of which are not pro-

portional to the kinetic energy of the light waves. While, therefore, a determination of the photometric and the relative radiometric values of the wave-lengths shows that the eye is selective in its response to wave-length, the results are not obtained in a form that will permit of a simple numerical comparison. To have done this by a photometric method the responses should have been brought to equality and the stimuli used to give the equal responses should have been estimated radiometrically instead of the converse procedure which was used in the preceding work. For with equal responses empirically determined and ratings of stimuli that can be put in a numerical scale, an expression can be given to the relative sensitivities which is itself numerical.

That is, in connection with the problem of the quantitative rating of sensitivities, it is scarcely necessary to point out that without a means of rating the stimuli which treats all wave-lengths alike or which in other words gives values directly in terms of kinetic energy, an estimate cannot be made of relative sensitivities which can be considered as quantitative. In other words, with the introduction of radiometric treatment of the stimulus in the various laboratories the possibility of a comparison of retinal sensitivities that can be considered as quantitative to a degree that would be acceptable in the rating of a physical instrument, has been presented for the first time. In addition, however, it is obvious that an equally important point to be considered in connection with the problem of rating sensitivities quantitatively, is what amounts of response can be employed with sureness of principle for the purpose. The amounts of response that can be determined with an acceptable degree of precision are, it will be remembered, equal responses, the threshold liminal and differential, equal sense differences, and the mean or average deviation of a determination of any one of these. Of these quantities the last can obviously be used with the least *a priori* sureness of principle in a quantitative rating of sensitivities, if, as we have stated, it is necessary in making the rating quantitative that we be able to compare numerically the amounts of response employed. The thresholds liminal and differential could conform to this requirement only on the assumption that they represent equal amounts of

response of the sense-organ. There is, however, no way of proving such an assumption. If they are accepted as equal, it must be on the grounds of logical self-evidence. Many, however, are unwilling to grant their equality on these grounds. Equality of response and equal sense differences seem alone, therefore, to be surely capable of numerical comparison as sensation quantities, and of these two the determination of the former is much the more feasible experimentally and has the much wider range of applicability. Now in the use of a sense-organ as a measuring instrument where several methods are proposed differing in sureness of principle, precision, range of applicability, etc., as is the case here, it is customary to choose the one having the greatest *a priori* sureness of principle as a standard and to check up the others against it. If hey give results which agree with it in the average their use s considered permissible. For example, in photometry the quality of brightness method is generally conceded to have ıe greatest *a priori* sureness of principle for the rating of ghts for the use of the eye and is accepted, therefore, as a andard for this purpose in terms of which to evaluate other ıethods which may have advantages of precision or conveni-ıce of application in certain situations. The problem of the ıantitative comparison of sensitivities seems to present an ıalogous case. The use of equal amounts of response seems have the greatest sureness of principle; but it is not appli-ble to all cases in which a quantitative rating of sensitivities desired. The use of the limen or just noticeable difference s, for example, a much broader applicability and its deter-ination has perhaps an advantage in precision when a com-rison is wanted between monochromatic stimuli differing in lor value. Obviously, therefore, a comparative study should made of the different possibilities of rating sensitivities in uations where all are applicable for the purpose of deter-ning whether or not a reasonable degree of agreement tains.[9] In our further work on the determination of the

Because of the lack of a simple relation between the response and nulus for a given wave-length or, more properly speaking, a small ge of wave-lengths throughout the intensity scale, and of a similar ition for different wave-lengths at corresponding points in this scale,

achromatic sensitivity of the eye to wave-length, this will be made a prominent feature of the study. Achromatic sensitivity is selected for this purpose because it is a case for which all the determinations mentioned above may be made.

Obviously in the development of methods of working in new fields—and the quantitative rating of sensitivities is from the standpoint of its degree of development, at least in vision, a new field—counsel should be taken of work and methods already well established. A pattern for the rating of sensitivities of sense-organs may be had in the practice with regard to the physical recording instruments. In the rating of the sensitivities of two galvanometers it may be pointed out, for example, that the sensitivity to each is expressed for comparative purposes by the amount of current that is required to produce one unit of deflection. Such a treatment of the sense-organ as a recording instrument is not possible unless it be assumed that its responses can be laid off in equal divisions or units. However, the underlying quantitative principle that both the amounts of response and amounts of stimulus must be numerically comparable is satisfied by making the comparison on the basis of equal amounts of response. While convenient it is by no means necessary that the results be expressed in unit terms. In short, the best that can be done is probably to accept equal responses as having *a priori* the possibility of quantitative comparison and evaluate the possibilities of other means of rating being strictly quantitative in terms of their agreement with this method taken as a standard.

The work of rating sensitivities based on a correlation of equal sensation responses and the energy values required to produce these responses brings us to our third type of comparison, namely, a comparison of the energy values of stimuli made photometrically equal. As an example of this method of

it is scarcely to be expected that a close agreement will be obtained in a rating of sensitivities made by the limen and just noticeable difference with that obtained when equal amounts of response are employed. However, a more definite knowledge is needed on the point before there can be any systematic treatment of the problem or a fair comparison and evaluation of results.

ating sensitivities Tables V-VIII and Charts IV-V have been repared.

In carrying out this work the lights were made photoietrically equal and their corresponding energy values were ieasured.[10] The stimuli were taken from a prismatic (CS_2)

TABLE V

Showing the change in the selectiveness of the achromatic response of ie eye produced by varying the intensity of light. In this table are ven the relative energy values of wave-lengths selected from seven fferent parts of spectra made photometrically equal at 75, 50, 25 and .5 meter-candles. The results of this and the following table represent so a determination of sensitivity by a method according to which both e amounts of response and the amounts of stimulus are numerically mparable. The comparative sensitivities for a given intensity should proportional to the reciprocals of the relative energy values given in is table for that intensity.

Stimulus	Relative energy value of stimuli at pupil of eye			
	75 meter-candles	50 meter-candles	25 meter-candles	12.5 meter-candles
Red (660 $\mu\mu$)	88.23	44.50	15.34	6.14
Orange (619 $\mu\mu$)	15.37	8.14	3.39	1.58
Yellow (582 $\mu\mu$)	6.44	3.47	1.55	0.744
Yellow-green (560 $\mu\mu$)	5.18	2.85	1.29	0.647
Green (523 $\mu\mu$)	9.65	5.29	2.41	1.114
Green-blue (502 $\mu\mu$)	25.89	15.54	6.04	3.02
Blue (469 $\mu\mu$)	100.00	53.54	24.04	9.62

) The method of working here is similar to that used by Nutting *ansactions Illumin. Engineering Society*, iv, 1914, pp. 633-643; also *losophical Magazine*, xxix, 1915, (6), pp. 301-309) in the determina- of what he has called the visibility curve for the eye, with the owing exceptions: (1) he used the method of flicker instead of the ility of brightness in making his photometric equalizations, i.e., a er balance instead of an equal sensation balance was obtained; and compatible with his problem, namely, the determination of the visi- constants for a group eye, more especially the principal one, the imum ratio of the candle to the watt, he used a greater number of rvers and a much greater number of points in the spectrum. As a l point, it may also be mentioned that apparently he has used no autions to obtain greater purity of light than is given by a single n spectroscope. (See footnote, 3, p. 283.)

sibility curves have been determined also by Thürmel (Das Lum-

spectrum of a Nernst filament operated at 0.7 ampere. They were narrow bands in the red (660$\mu\mu$), orange (619$\mu\mu$), yellow (582$\mu\mu$), yellow-green (560$\mu\mu$), green (523$\mu\mu$), blue-green (502$\mu\mu$), and blue (469$\mu\mu$). Four intensities of light were used, made equal respectively to 75, 50, 25 and 12.5 meter-candles, normal pupil. These higher intensities were selected because one of the objects of the investigation was to determine whether the selectiveness of the achromatic response to wave-length ceases at the higher intensities. Ives,[11] for example, determined his visibility curve at an illumination

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mer-Pringsheimsche Spektral-Flickerphotometer als optische Pyrometer, *Annalen der Physik,* 1910, xxxiii, (4), p. 1139) and H. E. Ives (The Spectral Luminosity Curve of the Average Eye, *Philosophical Magazine,* xxiv., 1912, p. 853). Both of these men used the method of flicker but neither measured the energies of his lights directly. An attempt was made by both to get the energies of the lights employed by the use of the eye as a selective radiometer. (On the use of the eye as a selective radiometer, see, for example, Lummer and Pringsheim *Jahresbericht d. Schles. Ges. f. vaterl. Kultur,* 1906, pp. 95-97; Beibl. 1907, p. 466.) Throughout his work on the determination of the visibility curve Ives seems to have followed very closely the method used by Thürmel two years earlier.

While the methods that have been used for determining the visibility curve are similar in general principle, with the exceptions just noted to that which we have outlined for a quantitative determination of sensitivities, it is not our understanding of that work that the lights were made photometrically equal for the reason that is given above, namely that if sensitivities are to be determined in a way that permits of numerical comparison the amounts of response as well as the amounts of stimulus used in making the determinations must be numerically comparable. The reason that is assigned by Ives (*Philosophical Magazine* xxiv, 1912, (6), p. 163), for example, is a technical one,—the photometric comparisons should all be made with the eye under the same illumination or in the same state of adaptation. In addition to this technical reason which is admittedly pertinent to the use of the eye in making any photometric balance between lights differing in color value we have considered it of significance to call attention to this other reason which is of much more fundamental importance, we believe, to the quantitative determination of sensitivities for any purpose whatever and which apparently has been overlooked.

[11] H. E. Ives. The Spectral Luminosity Curve of the Average Eye *Philosophical Magazine,* xxiv, 1912, (6), pp. 853-863. The use of artificial pupil by Ives does not seem to be a matter of design, but a condition imposed upon the work by his apparatus. He says, p. 856: "I

TABLE VI

Showing the change in the selectiveness of the achromatic response of [th]e eye to wave-length produced by varying the intensity of light. In [th]is table are given the reciprocals of the scale values in Table V. The [co]mparative sensitivity of the eye to the wave-lengths selected should [be] for a given intensity, directly proportional to the reciprocals of the scale [va]lues for that intensity.*

Stimulus	Reciprocals of scale values in Table VII			
	75-meter-candles	50 meter-candles	25-meter candles	12.5 meter-candles
Red (660 $\mu\mu$)	0.011334	0.02247	0.06519	0.16287
Orange (619 $\mu\mu$)	0.0651	0.12285	0.2950	0.6329
Yellow (582 $\mu\mu$)	0.15528	0.2882	0.6452	1.3441
Yellow-green (560 $\mu\mu$)	0.19305	0.3509	0.7752	1.5456
Green (523 $\mu\mu$)	0.10363	0.1890	0.41494	0.9009
Green-blue (502 $\mu\mu$)	0.0386	0.06435	0.01655	0.33113
Blue (469 $\mu\mu$)	0.01	0.01868	0.04160	0.10395

The reader is cautioned against attempting from these data to com[par]e sensitivities at different intensities. That is, while the amounts [of] stimulus are numerically comparable at the different intensities, ob[vio]usly the amounts of response are not.

[wh]ich he estimated to be about 25 meter-candles for his own [eye], normal pupil (300 meter candles falling on a pupillary ap[ert]ure of 1 sq. mm.), claiming that at this intensity the achro-

[T]he previous work an artificial pupil was used and the results were [give]n in terms of meter-candles illumination as viewed through this [1 sq.] mm. aperture [objective slit of spectroscope 0.5 x 2 mm.]. In [wor]king with a spectrometer the use of a small eye-slit is practically [imp]erative. But in practical photometry an artificial pupil of this size [wou]ld necessitate working at illuminations too high to be practicable [wit]h present illuminants if one had to attain the retinal illumination [calle]d for by the investigation here described. Were the pupils of all [obse]rvers of the same size under the same conditions, a reduction factor [migh]t be obtained so that the luminosity curve could be found with the [artifi]cial pupil and used for a corresponding illumination with the [natur]al pupil. Such, however, is not the case. In view of these facts [it wa]s considered advisable in the present research to have all curves [made] for a normal pupil illumination."

TABLE VII

Showing the change in the selectiveness of the achromatic response of the eye to wave-length produced by varying the intensity of light. In this table are shown in per cent of the original value, the energy value of the stimuli when their photometric values have been reduced from 75 to 50 meter-candles; from 75 to 25 meter-candles; and from 75 to 12.5 meter-candles. A high per cent energy value indicates that a relatively small decrease in energy is needed to produce the desired decrease in photometric value or that there is a relatively rapid darkening of the color with decrease of energy.

Stimulus	Per cent of energy value to original value when photometric value has been reduced from		
	75 to 50 meter-candles	75 to 25 meter-candles	75 to 12.5 meter-candles
Red (660 $\mu\mu$)	50.4	17.4	7.0
Orange (619 $\mu\mu$)	52.9	22.1	10.3
Yellow (582 $\mu\mu$)	53.8	24.0	11.5
Yellow-green (560 $\mu\mu$)	55.0	25.0	12.5
Green (523 $\mu\mu$)	55.8	25.0	11.5
Green-blue (502 $\mu\mu$)	60.0	23.3	11.7
Blue (469 $\mu\mu$)	53.5	24.2	9.6

matic response is practically, if not entirely, free from Purkinje effects. Nutting[12] for a similar reason used 350 meter-candles of light falling on a pupillary aperture of 1.465 sq mm., contending that this intensity of illumination is "safely outside the range of the Purkinje effect."

These views, however, it will be remembered, are quite the opposite from those of Helmholtz and others of the earlier writers who believed that the eye changes its selectiveness of response to wave-length with change of intensity of light at the higher as well as at the lower intensities of light. This conclusion is drawn from a statement made by them that beginning with a spectrum of fully saturated colors and increasing the intensity of light, all the colors are found to ten

[12] P. G. Nutting. The Visibility of Radiation. *Philosophical Magazine*, xxix, 1915, (6), p. 303.

TABLE VIII

Showing the change in the selectiveness of the achromatic response of he eye to wave-length produced by varying the intensity of light. In his table the comparative sensitivities of the eye to the different stimuli t a given intensity are shown in a scale in which the highest sensitivity or that intensity is represented by 100. If there were no relative changes the eye's sensitivity to wave-length with change of intensity of light or these high intensities, the values in this scale would be the same for ach stimulus for the four intensities.

Stimulus	Relative sensitivity in a scale in which the highest sensitivity is represented by 100			
	75 meter-candles	50 meter-candles	25 meter-candles	12.5 meter-candles
Red (660 $\mu\mu$)	5.87	6.40	8.41	10.54
Orange (619 $\mu\mu$)	33.72	35.01	38.06	40.95
Yellow (582 $\mu\mu$)	80.435	82.14	83.23	86.32
Yellow-green (560 $\mu\mu$)	100.00	100.00	100.00	100.00
Green (523 $\mu\mu$)	52.18	53.87	53.53	58.29
Green-blue (502 $\mu\mu$)	19.99	18.34	21.38	24.74
Blue (469 $\mu\mu$)	5.18	5.32	5.36	6.73

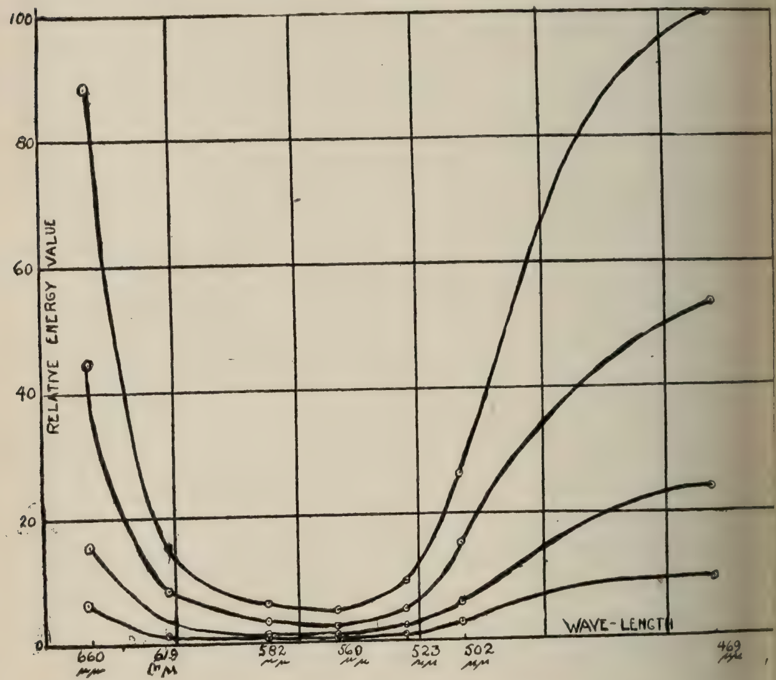
vards white and in so doing to change their luminosities at ferent rates.[13] (For example, see Helmholtz, *Poggendorff n. der Phys.*, 1852, *86*, p. 520; also *Handbuch der physioischen Optik*, 1896, 2te Aufl., pp. 465-466; A. Chodin, *mmlung phys. Abhandl. v. Preyer*, 1877, *1*, p. 33, ff., *Brücke, Sitzungsber. der Wiener Akad., Math.-Natur. isse*, 1878, *77*, (3), p. 63.)

ince in these as in all of the preceding determinations, a otometric value was wanted in terms of the power to arouse achromatic sensation as the eye normally sees its brights and not in terms of a flicker evaluation, the equality of ghtness method was used in making the photometric bale. That is, the comparisons are based on an equality of

In this connection it should be borne in mind that Nutting and presumably refer to determinations made by the method of flicker, e the writers referred to above are considering the eye as it nory sees its brightnesses.

CHART IV

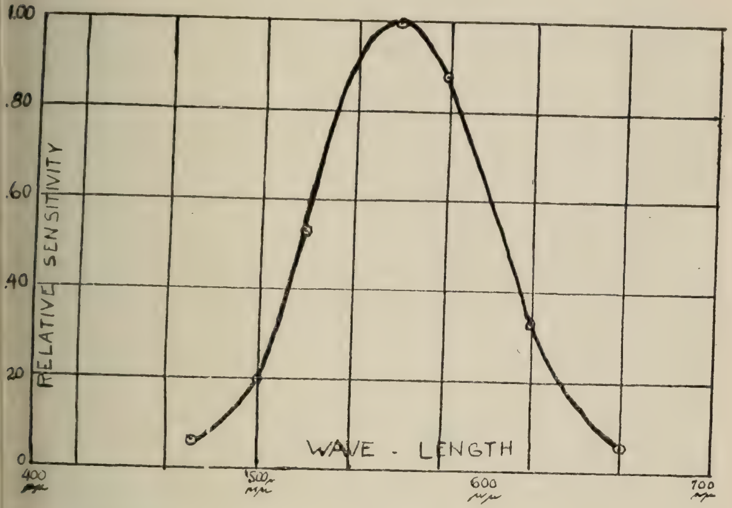
Showing the change in the selectiveness of the achromatic response of the eye produced by varying the intensity of light. In this chart are represented the relative energy values of wave-lengths selected from seven different parts of prismatic spectra made photometrically equal at 75, 50, 25 and 12.5 meter-candles.



brightness not a flicker balance. The plan of the apparatus used in making the photometric balance (spectroscope, photometric apparatus, etc.,) is indicated in Fig. I. The colored light was presented to the eye in the following manner. The eye-piece was removed from the spectroscope and a lens system was substituted consisting of two lenses L_1 and L_2, one to render the light emerging from the objective slit parallel and the other to focus it on the eye 30 cm. distant. By means of an extra set of jaws operating in the vertical, the length of the analyzing slit was reduced to a value which gave an image 3 x 1.49 mm. on the pupil of the observer's eye. This adjustment was maintained throughout the work. The size

CHART V

Showing a curve of achromatic sensitivity when the stimuli are made photometrically equal at 75 meter-candles.



the photometric field was limited by a screen S, containing stimulus opening 15 mm. in diameter. This screen was aced 20 cm. from the eye. Between this screen and the ns L_2 was inserted a small strip of metal, D, the inner edge which was carefully beveled. When adjusted to the position used in making the photometric observation, this edge st bisected the photometric field. The surface of this strip is kept freshly coated with magnesium oxide deposited from e burning metal. This surface received the light from the ndard lamp; the other half of the field was filled with light om the spectroscope. The spectroscope and lens system re shielded from the standard lamp by suitable screens. e photometric balance was obtained as follows. The standal lamp, a seasoned 32 cp. carbon lamp giving the color value the carbon standard of 4.85 watts per spherical candle, was at the position on the bar required to give the desired nsity of light in the photometric field, and the intensity of colored light filling the other half of the field was varied il a brightness match was obtained. The changes in the nsity of the colored light required to give the match were

not made by varying the width of the collimator slit, as is often the case, because changes in the width of the collimator slit tend to give a variable purity of light,—a condition which would have given us more trouble in the selection of our filters to absorb stray light. Specially constructed sectored discs with a single open sector adjusted by a finely threaded micrometer screw and provided with a Vernier reading to minutes, were used instead for this purpose. That is, the collimator slit was set at a width which made the comparison field slightly brighter than the standard field for the group of wave-lengths in question and the gelatines required to absorb the alien wave-lengths were placed in position over the analyzing slit. These gelatines, as stated earlier in the paper, were held in place by short clips fastened on either side of the slit to the

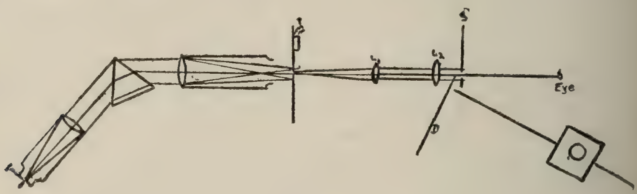


FIG. I

front surface of the jaws, the edges of which formed the slit. The width of the collimator slit and the gelatines were then kept constant, and the reductions needed to give the four intensities were made by means of the sectored discs, inserted between the analyzing slit and the lens L_1.

In Table V are given the relative energy values of the stimuli to give equal achromatic responses at the four photometric intensities used. These values are shown graphically in Chart IV. In constructing this chart as in case of all of the preceding charts, the wave-lengths are spaced to approximate the distribution in the prismatic spectrum. The comparative sensitivity of the eye to the groups of wave-lengths used should of course be as the reciprocals of the relative energy values required to give equal achromatic responses. The values of these reciprocals are given in Table VI. A graphic representation of the results for the highest intensity in this table is given in Chart V. In this chart for the sake of a closer

omparison with more recent work, the wave-lengths are given qual spacing along the abscissa and the scale employed (reiprocal at point of highest sensitivity = 1) is the same as as used by Nutting in his visibility curve.

In Table VII are shown in per cents of the values for 75 eter-candles the energy values of each of the group of wavengths when they have been made photometrically equal at), 25 and 12.5 meter-candles. In this table a high per cent. iergy value indicates that a relatively small decrease in engy is needed to produce the desired decrease in photometric ilue; or expressed in other terms, indicates a relatively rapid irkening of the color with decrease of energy. The results ow first of all, it will be noted, that change in selectiveness response with change of intensity is still present in the gion of the intensity scale included between 50 and 75 meterndles, as well as in the regions included between 25 and 75 eter-candles and 12.5 and 75 meter-candles. A closer scruiy shows further that in case of the reduction from 75 to meter-candles the most rapid darkening with a decrease of ergy occurs in the region of the blue-green. This effect is, will be remembered, quite the opposite of that which was tained at the lower intensities treated of earlier in the paper ee Table II, Columns 3 and 4). At these intensities the west darkening was obtained in the region of the blueeen and the most rapid in the region of the red. Moreover, the reduction 75 to 12.5 meter-candles, the region of most id darkening shifts to the middle of the spectrum. In rt, in passing from high to low intensities the region of st rapid change in selectiveness of achromatic response ms to shift from a region in the short wave-lengths at the h intensities, through the middle of the spectrum at the ermediate intensities, to the long wave-lengths at low insities. In Table VIII the change in selectiveness with nge in intensity is shown in still another way. In this le the comparative sensitivities of the eye to the different nuli at a given intensity of light are represented in a scale which the highest sensitivity for that intensity of light is itrarily given a value of 100. If there were no relative nge in the eye's sensitivity to wave-length with change of

intensity of light, the values in this scale would be the same for the four intensities of light. A more detailed investigation of this point for a greater number and range of intensities and for a greater number of points in the spectrum will be carried out later.

In conclusion we would again point out that the foregoing results are presented as preliminary and illustrative of some of the ways in which the selectiveness of the achromatic response of the eye to wave-length and its change with change of intensity may be studied by the help of energy measurements, rather than as a finished investigation of any one point. The work is discursive rather than intensive and in this regard was actuated by an entirely different purpose from that, for example, which has prompted the determination of the visibility constants for a group eye for the purpose of obtaining the mechanical equivalent of light, in which case a number of observers and a much greater number of points in the spectrum have been used. Moreover, since a sensation balance as the eye normally sees its brightnesses was wanted for the different intensities of light used, and not a flicker balance, all subjective equalizations of light intensities were made by the equality of brightness method. This choice of methods we consider alone compatible with the purpose of such studies as are here outlined, even were all other points of dispute waived with regard to the selection of a photometric method for other purposes and problems which may be encountered in the handling of light intensities.

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SOME AREAS OF COLOR BLINDNESS OF AN UNUSUAL TYPE IN THE PERIPHERAL RETINA

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At the psychophysical section of the first Congress for Experimental Psychology held at Giessen April 18–21, 1904, F. Schumann reported what he termed an unusual case of color blindness (his own).[1] So far as the ability to get the positive sensation is concerned, Dr. Schumann is, according to the report, totally blind to green and partially so to red.[2] In addition his case presents the following features. (1) While green light does not arouse a sensation of green, it does give red after-image and contrast sensations. Red light on the other hand gives a positive sensation but does not give either after-image or contrast sensations.[3] (2) A colorless mixed light can be matched by combining homogeneous red and green lights, but quite a little greater proportion of green is needed to give the neutral sensation than is required for

[1] Schumann, F., 'Ein ungewöhnlicher Fall von Farbenblindheit,' Bericht über den I. Kongress für experimentelle Psychologie in Giessen, 1904, pp. 10–13. See also G. E. Muller's discussion of the report, *ibid.*, pp. 20–21.

[2] His diagnosis that he is partially sensitive to red was based on two facts. (*a*) Red in the region of 670 $\mu\mu$ gave a sensation which was plainly different from yellow and could not be matched by a full spectrum gray. And (2) orange which to the normal eye appeared distinctly reddish, appeared to him a pure yellow. From this point in the orange towards the short wave-length end of the spectrum three qualities were sensed: a yellow, a blue and a band between them which could be matched with a full spectrum gray. On these facts was based the diagnosis of blindness to green.

[3] While a red light does not give green contrast sensation, it does produce an effect on a neighboring field which raises the threshold or diminishes the sensitivity to red. That is, a gray ring on a red ground appears gray but an amount of red can be added to it without being sensed which is supraliminal when red is not present in the surrounding field. In other words a physiological induction seems to be present which inhibits the complementary excitation although the induced excitation does not itself arouse sensation. We have here, therefore, another evidence that the complementary and induction relations between red and green are intact, the ability of the green excitation to arouse sensation alone being absent.

the normal eye. And (3) a yellow of the spectrum can be matched by the combination of a red and green if properly selected. In this case also a considerably greater proportion of green is needed than is required for the normal eye.

One of the writers[1] mentioned several years ago in a partial report of a somewhat extensive investigation of the color sensitivity of the peripheral retina that small areas could be found in the periphery of the normal retina showing characteristics for the colors red, green, yellow and blue similar to the Schumann case for red and green. That is, areas may be found which are totally blind or deficient to one of these colors so far as the positive response is concerned, but which seem not to be correspondingly deficient in the after-image and complementary or cancelling reactions. In fact, so far as can be told, the after-image and complementary reactions are no different in these areas from those in the immediately adjacent normal portions of the retina. We found it infeasible to test for a contrast reaction in these comparatively small and remote areas. Since that time an examination has been made of the eyes of a number of observers, more especially in connection with the work of the undergraduate laboratory, with the result that although observers may differ widely with regard to the number of the spots, their location, and the color responses affected, we are inclined to believe that the presence of such spots in the peripheral retina may be considered the rule rather than the exception.

A successful search of the peripheral retina for spots of the kind described above requires some means of making a rather minute investigation from center to periphery in a number of meridians. In our own work the rotary campimeter has been employed as a means of presenting the light to the different parts of the retina and the investigation has been made both with pigment papers and with the light of the spectrum as stimuli. In case the light of the spectrum was used, a very intensive stimulation was given. The lights were narrow bands taken

[1] Rand, G., 'The Factors that Influence the Sensitivity of the Retina to Color,' *Psychol. Rev. Monog.*, 1913, *15*, footnote, pp. 108–109. See also Ferree and Rand, 'A Note on the Determination of the Retina's Sensitivity to Colored Light in Terms of Radiometric Units,' *Amer. Jour. of Psychol.*, 1912, *23*, p. 331.

from the spectrum of a Nernst filament (corrected for impurities) operated by 0.6 ampere of current, and was of the order of intensity at the eye of 11.14×10^{-8} watt per sq. mm. for the red; 9.676×10^{-8} watt per sq. mm. for the yellow; 1.285×10^{-8} watt per sq. mm. for the green; and 0.878×10^{-8} watt per sq. mm. for the blue. The total amount of light entering the eye was in each case respectively 36.76×10^{-8} watt; 31.93×10^{-8} watt; 4.24×10^{-8} watt; and 2.90×10^{-8} watt. Lights of this intensity for the same observers were sufficiently strong, for example, to be sensed as color clear out to the limits of white light vision for all the colors but the green; and the green, it may be mentioned, could not for the observers used be made to coincide with the limits of white light vision whatever intensity of light was employed. The only effect of these greater intensities was to narrow in some cases the area of the spots previously mapped by means of the pigment paper stimuli. Thus it seems that the totally blind area is frequently bounded by a zone of weakened sensitivity. The investigation was made with three conditions of surrounding field: a gray of the brightness of the color, white and black. The only effect of the white and black surrounding fields was to increase the size of a spot mapped with a surrounding field of the gray of the brightness of the color. A preëxposure of a gray of the brightness of the color was used in each case. Care was taken to keep the intensity of the illumination of the room accurately constant throughout the investigation.

In testing for the after-image reaction, a few seconds of preëxposure was given to a gray of the brightness of the color previous to the color stimulation. The color stimulation was given for 3 sec. and the after-image projected on a gray of the brightness of the color, placed in the path of the colored light just behind the campimeter-opening. The intensity of after-image was compared as well as could be with that obtained with the same intensity and conditions of stimulation on the immediately adjacent portions of the retina. So far as could be told there was characteristically no difference between the strength of the after-image reaction in the spot itself and in

the immediately surrounding retina. In the investigation of the complementary or cancelling reaction, a combination of the complementary colors to gray was made for the surrounding portions of the retina and this stimulus was presented to the color-blind area. In each case it was seen as gray, not as the color complementary to that for which the spot was blind. We need scarcely point out that in making this test it was necessary to determine whether the amount of colored light employed would have aroused color sensation had it not been combined with its complementary color. This was done in two ways: (*a*) The amount of color used to form the combination to gray was presented to the color-blind area, combined with the proper value of a substitute sector of the gray of the brightness of the color to which the area was blind; and (*b*) the threshold was determined in the color-blind area for the color complementary to that to which the area was blind, and its value compared with the amount used in making the combination to gray. The results of both determinations showed that a true complementary action was present.

The peripheral retina spots while similar in a general way to the case described by Schumann present the following points of difference. (1) There was no detectable weakening of the sensitivity to the complementary or antagonistic color in the areas in question. And (2) no more of the color to which the area was blind was required to combine to gray with the antagonistic or complementary color than was needed on the normal areas of the retina immediately adjacent.

In the presentation of results space will be taken for only two observers, selected because of rather wide differences in the number, size and location of the spots. In Chart I. is shown results for Observer R. and in Chart II. for Observer C. The Hering pigment papers were used as stimuli and the investigation was made with surrounding field and preëxposure of the brightness of the color in each case. The limits of sensitivity were determined for each color in 16 meridians and these points are connected to give outline maps of color sensitivity for stimuli of the intensity used. In working in any of the above-mentioned meridians the stimulation was given at points

separated by no more than 1°. When a gap or a significant depression in sensitivity was found, the campimeter was rotated and the investigation made in a sufficient number of near-lying meridians to give a careful outline of the deficient area. These areas are represented on the charts in black, with letters to indicate the colors to which there is a deficiency. In case there is total blindness to the stimulus used, the spot is repre-

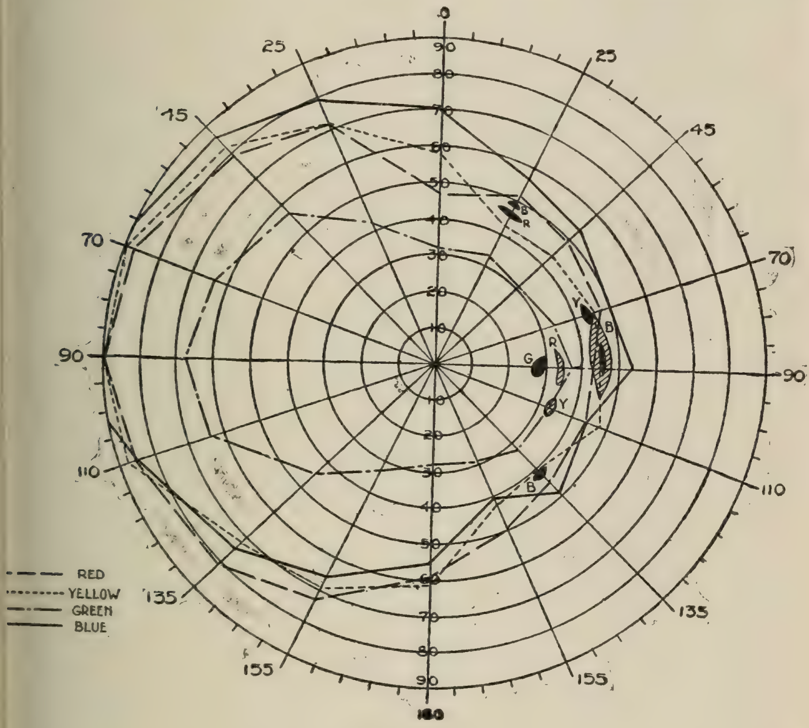

CHART I

Showing for Observer R the Areas of the Peripheral Retina having the Schumann ype of Color Blindness. These areas are represented in black, with letters to indi- te the colors to which there is a deficiency. In case there is total blindness to the mulus used, the area is represented in solid black; in case there is only a marked pression of sensitivity, the area is shaded. In this latter case areas are represented ly when the depression amounts nearly to blindness. The only effect of using ectrum lights of very high intensity: red (670 $\mu\mu$), 36.76×10^{-8} watt at pupil of e; yellow (581 $\mu\mu$), 31.93×10^{-8} watt at pupil of eye; green (522 $\mu\mu$), 4.24×10^{-8} tt at pupil of eye; and blue (471 $\mu\mu$), 2.90×10^{-8} watt at pupil of eye, was to rrow in some cases the area of the spots previously mapped by means of the gment paper stimuli.

sented in solid black; in case there is only a marked depression of sensitivity the area is shaded. In this latter case areas are represented only when the depression of sensitivity amounts nearly to blindness. They were, for example, so insensitive that the color response could not be aroused when an unfavorable brightness of surrounding field or preëxposure was used.

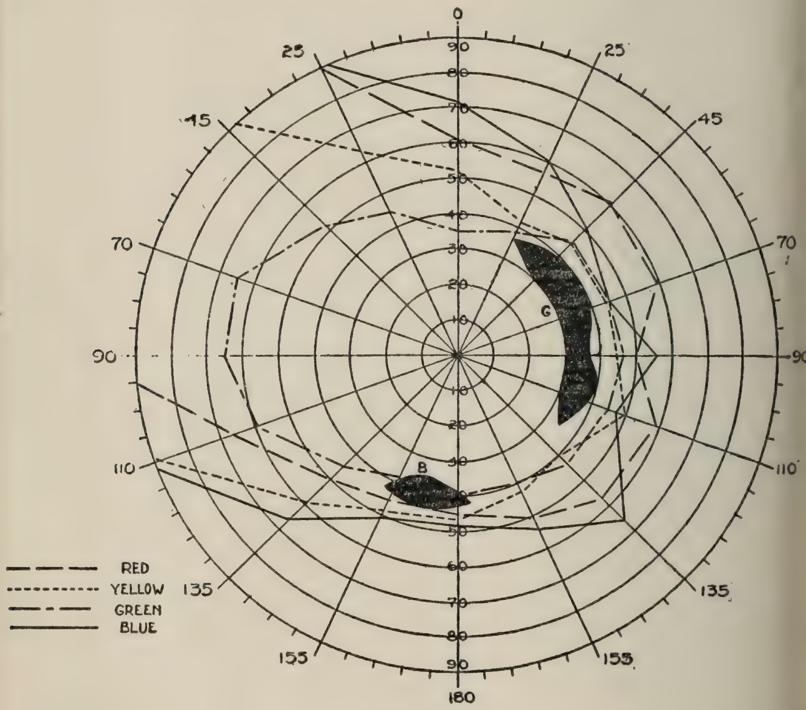

CHART II

Showing for Observer C the Areas of the Peripheral Retina having the Schumann Type of Color Blindness. The conditions of investigation and method of representation is the same in this chart as in Chart I. The results for Observers R and C are selected for presentation here because of the somewhat unusually wide difference that was found in the number, size and location of their spots.

In discussing his own case, Schumann seems to think that the phenomenon indicates that there must be more than one functional level involved in the production of visual sensation: peripheral or sub-cortical, and cortical. One of these, the peripheral or the sub-cortical, is the locus of the complementary or cancelling action, and the after-image and contrast reac-

tions. Green light in his case arouses these three reactions because the level concerned in producing them is functionally normal. Green does not arouse the positive sensation, however, because there is functional deficiency in the remaining level or levels. G. E. Müller, who also made supplementary tests and experiments on Schumann and discussed Schumann's report at the Congress in Giessen, concurs strongly in the conception that more than one functional level is needed to explain the Schumann case. At this same Congress Müller[1] discusses seven types of color-blindness which he further believes can be explained best on the conception of more than one specific functional level, the processes of which may be separately deficient. His theory of color vision is in fact here elaborated to include both peripheral and central visual processes. While we have no wish to engage in theoretical discussions at this stage in our own work, it may not be out of place, in addition to the results presented in this paper, to call to mind in this general connection our experiments of the effect of the achromatic excitation on the chromatic which seemed to indicate very strongly that this effect both quantitative and qualitative takes place at some level posterior to that of the cancelling, after-image, and contrast reactions.[2] We have also obtained other results, as yet unpublished, on contrast induction in the far periphery of the retina which seem to indicate that the deficiency which for these portions of the retina prevents the color stimulation from producing sensation is in part at least posterior to the level at which induction takes place. Moreover, unless the complementary action were intact in case of

[1] Müller, G. E., 'Die Theorie der Gegenfarben und die Farbenblindheit,' Bericht ber den I. Kongress für experimentelle Psychologie in Giessen, 1904, pp. 6–10. he conception of a central deficiency was used as early as 1868 by Niemetschek to xplain color blindness (*Prager Vierteljahrschrift*, *100*, p. 224).

[2] The results of these experiments have as yet been published only in part. (See An Experimental Study of the Fusion of Colored and Colorless Light Sensations. he Locus of the Action," *Journ. of Philos., Psychol. and Scientific Methods*, 1911, *8*, p. 294–297.)

The fuller publication has been delayed for one reason because we have felt the eed of giving a somewhat exhaustive résumé of the work that has yet been done on the bject. This work has been so scattered and unsystematic and so much of it appears dden under titles that give no indication that it is there, that the work of compiling as been somewhat time consuming.

blindness to one color over a whole or part of the retina, it would seem that white light should always be sensed by the subject in the tone complementary to that for which the blindness exists.[1] Or to put the matter more conservatively in terms of color-blindness testing, it would seem impossible ever in such cases to match a full spectrum gray to the color to which the subject is blind, or to all combinations of complementary colors, or to any in fact except the pair to one member of which the defect exists.

In the study of the eye as a recording instrument it is always a helpful feature to take our start from the physical recording instruments which respond to light. Not only are the characteristics of a given one of these instruments more accessible to study than the eye, but the instrument itself can be changed and the effect produced be noted. Also different types of instrument are accessible to study. Just as the simpler work on the study of the physical instruments serves as a helpful methodological guide in the experimental determination of the characteristics of response of the eye, so may we get methodological helps from the study of these instruments which may be of service in forming our conceptions of the actions and functional relations of the cerebro-retinal structure.

One of the characteristics of the instruments which respond to radiant energy is with the exception of the photographic plate a surface or layer in which the energy of the light-wave is transformed into an effect which it is the function of another part of the apparatus to record. This transformation, moreover, in case of some of these instruments: the selenium cell, the photoelectric cell and the photographic plate, is selective;

[1] It is possible that an alternative explanation of the above point may be found in some of the other types of modification of existing theories, *e. g.*, Fick's and Leber's modification of the Helmholtz theory to explain the variations in the color sensitivity of the peripheral retina (see Fick, A., 'Arbeiten aus dem physiol. Laborat. der Würzburger Hochschule,' pp. 213–217; Leber, T., *Klin. Monatsblätter f. Augenheilk.*, 1873, *11*, pp. 467–473). The conception of different functional levels, however, should at least be recognized as one of the possibilities of explanation for monochromatic deficiencies, and as a very plausible and perhaps necessary assumption to explain phenomena of the kind described by Schumann and by the present writers in this paper.

i. e., it is different in amount for the different wave-lengths[1] and the selectiveness varies with the intensity of light used. There is an analogue to this in the selectiveness of the achromatic response of the eye to wave-length and the variation of this selectiveness with change of intensity of light. (In case of the achromatic response this is known as the Purkinje phenomenon.) Some of these instruments also show like the eye a lag in coming to their maximum of response, a fatigue effect, and an after-effect. All of these effects are characteristic of the receiving part of the instrument, not of the recording mechanism. The final form into which the response of the instrument is put is, however, a function of the recording part of the apparatus. Moreover, either one of these parts of the apparatus may, we scarcely need point out, be separately deficient without the impairment of the other. In view of the general similarity in characteristics of response shown between the eye and these instruments, it would not seem entirely unreasonable to suppose,[2] therefore, even in advance of a decisive amount of the evidence which seems to be accumulating, that the visual apparatus consists of receiving and recording parts or levels both of which are necessary to the final response, but either of which may be separately deficient without impairment of the function of the other.

[1] Griffith, I. (*Phil. Mag.*, 1907, *14*, (6), p. 297) working with ultra-violet radiations nd Dember, H. (*Ber. d. kgl. sächs. Akad. d. Wiss.*, 1912, *64*, p. 266) working with the isible spectrum both claim that the photoelectric cell is selective in its response to ntensity of light. Elster and Geitel (*Phys. Z.*, 1913, *14*, p. 741; 1914, *15*, p. 610) owever, found a constant relation between intensity of light and the response of the ell except in case of very intense light. For a fuller discussion of this point see erree and Rand, *Psychological Review Monographs*, 1917, XXXII, (5), p. 46.

[2] It will be understood that an analogy between the eye and the physical recording istruments is attempted here primarily as illustrative rather than as argumentative.

POWER OF THE EYE TO SUSTAIN CLEAR AND COMFORTABLE SEEING WITH DIFFERENT ILLUMINANTS.

By C. E. Ferree, Ph. D., and G. Rand, Ph. D.

BRYN MAWR COLLEGE.

previous papers[1], a study has been made of the effect on the eye of differences way in which light is delivered to it from a given type of illuminant. In ork of the present paper a series of tests is begun on the effect of the illuminant Eleven of the more common illuminants have been tested with the same condiof installation, shading, etc., and a correlation has been made between the lighting obtained and the power to sustain clear and comfortable seeing.

INTRODUCTION.

e belief seems to prevail among n and not a few technical and al men that the kerosene flame as rce of light possesses advantages e eye not to be had by other inants, more particularly the inscent solids. At one of the earlier ngs of the American Medical Astion's Sub-committee on the Hyof the Eye, the belief was exd and quite favorably received of all of the common illuminants rosene flame gives the best light e eye and that it should be taken r model for hygienic lighting. inent ophthalmologist writes[3]: "It en shown by experiment that the which gives the maximum of illuion with the minimum of irritao the eye is composed of the yel rays of the middle of the spec For this reason the old fash candle and kerosene lamp have gone entirely out of fashion." In re recent article[4] in the same l we find a section on "Simulating luminants," and in the last paper efore the Philadelphia section of uminating Engineering Society a ng sentiment for the older illumiwas noted.[5]

ving out of consideration the things that have been said in popular and semi-technical publications on the effect on the eye of the color value of light, of which subject we do not wish to make a special point prior to experimentation, these are only a few of the more familiar statements of opinion that may be cited in evidence that there is a need for testing the effect on the eye of the light of the older illuminants (more especially the kerosene flame) as compared with the more modern illuminants with the intensity, conditions of shading, installation and use, etc., the same in each case.

Two divisions may be made of this comparison: (a) with the illuminants compared used for the purpose of general illumination, and (b) with these illuminants adapted to local, reading table or desk lighting. In the first of these cases differences in result would perhaps be more apt to occur, because of the greater number and complexity of the factors present and the greater difference in difficulty in protecting the eye from unfavorable conditions relating to a set of factors which we have hitherto called the distribution factors. It is quite probable also that a comparative rating of illuminants made on the basis of local lighting, in which case it is not difficult, for example, to eliminate high brilliancies from the field of view, will not hold for general

lighting, in which case the chief difficulty seems to be to protect the eye from high brilliancies.

Because, however, of the greater difficulty in getting comparable installations for general lighting, we have chosen to make the first series of tests with local lighting given by a single unit, a one-burner student lamp of the standard type with modifications suitable for the different illuminants employed. We have been led to choose this particular type of unit in part because the belief in the superiority of the kerosene flame for the eye is in the minds of those we have questioned associated largely with the lighting effects given by the student lamp; and in part because this lamp is well adapted for the control of conditions under which we wish the first series of tests to be made.

CONDITIONS TESTED.

Two series of experiments were conducted. In the first series the illuminants tested were a kerosene flame; a 50-watt, clear, metallized filament (Gem) carbon lamp; a 15-watt, clear, "mazda, type B" tungsten lamp (round bulb); a 60-watt, clear, "mazda, type B" lamp; a 75-watt "mazda, type C" lamp; and a 75-watt "mazda, type C-2" lamp.* The kerosene flame (Lusterlite kerosene) was burned at a height of 3 inches and had a horizontal candlepower of 15.8. For the sake of comparison with the kerosene flame it might have been desirable to have conducted the tests with the other illuminants equal to it photometrically, or approximately so, as well as with an equally illuminated reading page and test object. This was, of course, impracticable in case of the "mazda, type C" lamps. For this reason two "mazda, type B" lamps were used,—one as nearly as possible equal in candlepower to the kerosene flame, the other to the two "type C" lamps.

In choosing the sources, care was taken also to have them all as nearly as possible of the same size or to have a check condition on this factor [illegible] gous to that described above; a[illegible] adjust the position of the lamp sc[illegible] sustain approximately the same[illegible] tion to the shade. The bottom [illegible] shade was, for example, in each[illegible] 2.5 cm. below the center of the [illegible] nous source.

The lamp was placed behind [illegible] the left of the observer in the p[illegible] that was judged by several obser[illegible] give the most favorable conditio[illegible] reading. This position may be r[illegible] specified as follows: The angle[illegible] the median plane of the observer[illegible] by a plane passing vertically th[illegible] center of the unit was approxima[illegible] degrees; and the line in the latte[illegible] connecting the bottom of the [illegible] with the center of the reading[illegible] formed an angle of approximate[illegible] degrees, with the horizontal plan[illegible] ing through the center of the r[illegible] page. The reading page was sup[illegible] by a rack fastened to the upri[illegible] which was attached the mouth[illegible] used by the observer in taking [illegible] min. record before and after [illegible] This rack was inclined at an a[illegible] approximately 30 degrees with t[illegible] tical. To insure that the same [illegible] of light fell on the reading page [illegible] case, the brightness of the pa[illegible] measured before and after w[illegible] means of a Sharp-Millar illumin[illegible] with the test plate removed a[illegible] brated to give readings dire[illegible] candlepower per square inch.

The changes needed to give e[illegible] of illumination on the readin[illegible] were made by changing the d[illegible] of the lamp from the page. [illegible] changes in case of the first thr[illegible] minants were very small. For [illegible] mainder, owing to the greater [illegible] ence in the candlepower of th[illegible] used, the equalization required [illegible] greater difference in the distanc[illegible] lamp from the reading page [illegible] ployed. This meant a slightly [illegible] difference in the amount of [illegible] illumination given and a

*Trade definitions: Gas-filled, *daylight* (blue) glass incandescent lamp—Mazda C[illegible] filled, clear glass incandescent lamp—Mazda C. Vacuum, clear glass incandescen[illegible] Mazda B.

er difference in the brightness of urroundings. That is, the lamps igher candlepower, placed at a ier distance from the reading page, inated a larger field than the s of lower candlepower. In mak- iese changes of distance care was to keep the angle at which the fell on the page in all cases the Some difficulty was given also

"mazda, type B" lamp and an Ivanhoe-Regent steel reflector of the intensive type, aluminum lined, were used, placed in front and to one side of the test object at the distance and angle needed to give the required illumination. In order that the test object alone should be illuminated and not the surrounding wall, objects, etc., the opening of the reflector was covered, and an

FIG. 1.

I: Room showing position of source of light (student lamp) reader and page, in measuring the power of the eye to sustain clear and comfortable **vision.**

difference in the length of the employed. For example, the ems of the "type C" lamps made ssary that the shade be raised if aments were to have approxi- the same position in the shade e had by the kerosene flame and ments of the shorter lamps. To ıre of the needed adjustment in ight of the shade an extension holder was used.

ng to the angle of direction of nt and the distance of the lamp, t object had to be illuminated separate source. For this a

oblong aperture was cut of the size and shape needed to give the cross section of light desired. The position of this aperture in the opening of the reflector was chosen with reference to giving the most even illumination of the test object. That is, the light was not taken directly from the lamp but from the most favorable part of the inner surface of the reflector. The test object was made to match the reading page both in brightness and color value.

The match in color value was secured by means of thin gelatin filters covering all or a part of the aperture. If only

a part of the aperture was covered, the filter was used as a diaphragm with an opening similar in shape to the original aperture. There was, for example, enough difference in the color value of the illuminants that without this match a colored after-effect was given, distinctly different from the reading page. This would have necessitated that the final 3-min. record be taken in part at least with a test object having a coloration complementary to the reading page, which would not have been compatible with the purpose of the test. Before beginning each test of the series, the eye was allowed the customary adaptation period without work under the illumination to be tested. The choice of the length of adaptation period was empirical, based on a series of acuity tests, the object being to determine a period the prolongation of which gave no further change in acuity.

In the first series of tests with the illuminants mentioned above, the ordinary green shade of the student lamp was used. However, as the work progressed, the results seemed to indicate more and more clearly that difference in color value must be added to the list of factors which are considered to affect the power of the eye to sustain clear seeing for a period of work. In fact, as the tests were conducted, color value was the only variable of any magnitude present from series to series. In any event it was considered advisable to repeat the tests with the color value proper to the illuminant, unmodified by the light which filtered thru the shade, even tho the position of the lamp was such that a very small part of the light which fell on the reading page was of this origin. From this time on, therefore, an opaque shade of the same size and design and with a neutral lining was substituted for the green shade. The results for the neutral shade only will be given in this paper, altho no significant difference in result between the green and the neutral shade was found.

The reading page illuminated by the different lights had the following color values: the "mazda, type B" lamp, an unsaturated reddish yellow; the kerosene flame, reddish yellow with a greater proportion of red and more urated; the carbon lamp, reddish low with less red than the kero flame and more than the "type lamp; the "type C" lamp, unsatu yellow, nearly white; and the " C-2" lamp, noticeably bluish. T estimates of color value are bas part on a direct comparison, in on the filters that had to be use make the color match between th object illuminated by the "typ mazda lamp and the reading lighted by the illuminant to be t We have not as yet made a sta colorimetric or spectrophotometric parison.

The tests were conducted in a 16 ft. 6 in. (5.03 m.) long, 11 ft. (3.58 m.) wide and 9 ft. 6 in. (2.9 high. A photograph of the room an observer, lamp and recording ratus in position is shown in F The recording apparatus and th tures for lighting the test object will be noted, screened from th server's view.

In the selection and use of obs for all of our work care has been cised in the first place to choose those who had already shown a factory degree of precision in work in physiologic optics and clinic record showed no uncor eye defects of consequence. Al been under 30 years of age. Bef ing allowed to take part in the work of testing, each observe trained to a satisfactory degree cision in the 3-min. records u given lighting condition and in hour test under several conditio the actual work of testing, the were compiled from a number of vations and the precision was c up by the size of the mean va No results were accepted as sign unless the variation produc changing the condition to be test largely in excess of the mean e mean variation for each co tested. This, the accepted check influence of variable extraneous in work of this kind, was carefu plied at each step in the work. A statement of the precautions th

Type of Illuminant	Dominant Color	Brightness (cp. per sq. in.) Test object	Brightness (cp. per sq. in.) Reading page	Time	Working distance (cm.)	Total time clear (sec.)	Total time blurred (sec.)	Total time clear ÷ total time blurred	Ratios reduced to common standard	Loss of efficiency expressed in percentage change of ratio	Mean variation (per cent.) Based on 3.5	Mean variation (per cent.) Based on result sought (drop in ratio)
Mazda lamp, Type C..........	Unsaturated yellow, nearly white.	0.003168	0.003344	9 A. M.	60	144.27	35.73	4.038	3.50	5.34	0.19	3.58
				12 M.	60	142.67	37.33	3.822	3.313	....	....	....
Mazda lamp, Type B, 60 W....	Unsaturated yellow, slightly reddish.	0.003168	0.003344	9 A. M.	60	139.0	41.0	3.39	3.50	6.86	0.43	6.25
				12 M.	60	136.7	43.3	3.157	3.26	....	....	....
Mazda lamp, Type B, 15 W....	Unsaturated yellow, slightly reddish.	0.003168	0.003344	9 A. M.	60	138.6	41.4	3.348	3.50	7.11	0.503	7.07
				12 M.	60	136.2	43.8	3.11	3.251	....	....	....
Carbon lamp (metallized filament).	Reddish-yellow	0.003168	0.003344	9 A. M.	60	142.5	37.5	3.80	3.50	7.89	0.371	4.71
				12 M.	60	140.0	40.0	3.50	3.224	....	....	....
Kerosene flame	Orange-Yellow	0.003168	0.003344	9 A. M.	60	139.17	40.83	3.408	3.50	8.39	0.323	3.84
				12 M.	60	136.33	43.67	3.122	3.2063	....	....	....
Mazda lamp, Type C-2........	Unsaturated blue ..	0.003168	0.003344	9 A. M.	60	138.75	41.25	3.364	3.50	13.14	0.60	4.57
				12 M.	60	134.12	45.88	2.923	3.04	....	....	....

TABLE II.

Showing a comparison of the tendency of the different illuminants used to cause loss of visual efficiency and to produce ocular discomfort. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

Type of Illuminant	Dominant Color	Brightness (cp. per sq. in.) Reading page	Per cent loss of efficiency	Mean variation (per cent)	Time threshold of discomfort in seconds (reading)	Mean variation (per cent)	Change produced by changing type of reflector (per cent)
Mazda lamp, Type C............	Unsaturated yellow, nearly white.....	0.003344	5.34	0.19	116.5	1.30	.....
Mazda lamp, Type B, 60 W........	Unsaturated yellow, slightly reddish..	0.003344	6.86	0.43	98.5	1.53	15.45
Mazda lamp, Type B, 15 W........	Unsaturated yellow, slightly reddish..	0.003344	7.11	0.503	98.5	0.51	0
Carbon lamp (metallized filament).	Reddish-yellow	0.003344	7.89	0.371	93.0	0.72	5.58
Kerosene flame	Orange-yellow......................	0.003344	8.39	0.323	90.0	1.11	3.23
Mazda lamp, Type C-2..........	Unsaturated blue	0.003344	13.14	0.60	54.5	3.70	39.44

been used in this and previous work to secure reproducibility of results has been given in various places in preceding papers.[6]

The results for the effect on the eye are given in Table I. The values given in this table are averaged in each case from the results of a number of three hour tests. In order to show the reproducibility of the results obtained and to determine whether the variations produced by the changes in lighting effects are safely in excess of the variations in the test itself, subject to all of the variable factors which may influence it, the mean variation from the average result has been computed in each case. The value of these in per cent is given in columns 12 and 13 in Table I. This value has been estimated in two ways. In column 13 it is based on the result sought, namely, the mean value of the drop in ratio of time seen clear to time seen blurred. Computed in this way the results indicate whether or not each individual determination has been made with an acceptable degree of precision as compared with other work of its class. In column 12 it is based on 3.50, the value of the ratio time clear to time blurred, which has been chosen empirically as the standard of performance of the eye in the 3-min. record before work. Computed in this way, the results appear in a form from which it can readily be determined whether or not the work has been done with a degree of precision which is acceptable for the comparative work which is the special purpose of these experiments. That is, to be acceptable in this regard, the v of the drop in ratio caused by the conditions to be tested, each case be safely in exces mean variation. To make this son convenient, the drop in r the mean variation have both timated in per cent on the sa 3.50.

In Fig. 2 a graphic represe made of the results of Table I. structing this chart the total the test period is plotted a abscissa and the ratio of the test object is seen clear to th is seen blurred is plotted along nate. Each numbered divisic along the abscissa represents of the test period; and along nate, an integer of the ratio.

In former papers another r evaluating the results of the employed in addition to the above. In this method the ra time seen clear to the total ti observation is taken as the n the eye's ability to sustain cl at the time the test was taken sake of again comparing this evaluation with the one used chart has been prepared (om this paper because of lack of which the ratio of time clea time of observation is plott length of test period. A com this chart with that given shows the same order of rat illuminants, but a slight dif the position in the scale give of them. For the purpose o ing what is the best way of t

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(1) The data given in this paper were obtained from the observer whose been given in the preceding papers on the effect of different conditions of ligh eye. In case of the present paper we have not as yet, for lack of time, been a up these results with those obtained from other trained observers. We hav in the work on the distribution factors always found the results of this obs typical of the group of observers used. Whether or not this will be the ca in which the distribution factors are not the sole or principal variable, remai determined. In this regard it is perhaps only fair to say that the character sponse of the eyes for which these results are given. have been very widely They have been chosen especially for their normality and practiced precisi vior, and have been used in these experiments under conditions of control bas unusual and widely tested knowledge of the factors which influence their s response. Data on their characteristics of response may be found in more th ticles. Their spectral luminosity curve, for example, agrees very closely wi age curve obtained by Nutting for 21 observers.[5]

The results of the above tests are now being checked up on other traine

s of the tests, several methods been employed. Up to and ing the present paper, however, hree of them have been given in ratio of time clear to time d, ratio of time clear to total time servation, and the per cent drop ratio time clear to time blurred.[1] timate decision with regard to s the best method of treating the has not yet been reached and determinations were made and a discussion of the method that was used has been given in a previous paper. The results are shown in Table II. In this table are given, also, for the sake of comparison, results expressing the tendency of each type of illuminant to cause loss of ability to sustain clear seeing.

The results of this work, so far as it has been carried, more particularly

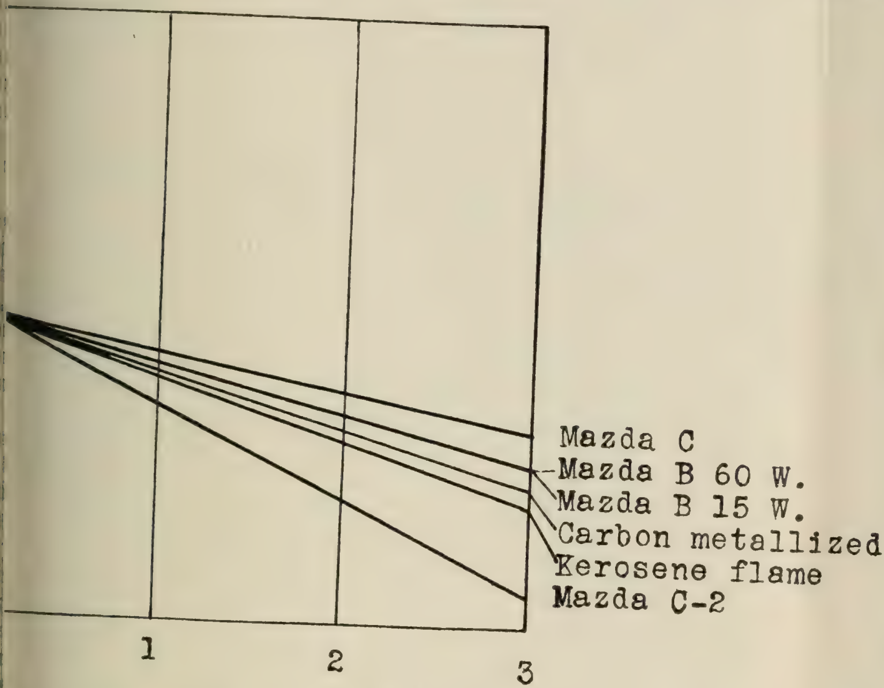

Fig. 2.

c representation of results of Table 1, each numbered division at the bottom represents one e test period. The lines start from the assumed base of 3.5, showing loss in ratio of time clear urred.

urposes of this work is perhaps essary. From the data given of them may be used.

rmerly, the work was cony determining for the different nts used the relative tendencies ce ocular discomfort with the ork. A description of how the those to be presented in a later paper which cover a range of color values greater in amount and apparently more significant in direction, seem to indicate that the tests for the effect of color value of light on the power of the eye to sustain clear and comfortable seeing should be carried further. In the work

comparison of this chart with those of the preceding papers shows that the orgnitude of loss in power to sustain clear seeing for the kerosene flame and B mazda lamp (student lamp unit), was about the same as for the best of the verted reflectors (Type B mazda lamp); and for the Type C-2 lamp as for the e translucent inverted reflectors. The effect for the Type C mazda lamp was etter than for the best of the opaque inverted reflectors.

so far we have found that in case of a given color this power decreases with increase of saturation of color; but that independent of saturation some colors affect the eye more than others. The worst effects thus far have been obtained with colors towards the short wave-length end of the spectrum. The reading of black letters or other characters on a page which presents any considerable degree of coloration is a peculiarly baffling experience. There is an unclearness which is not the blurring of bad focusing or of faulty fixation, but which seems to be a matter of the ease or, rather, lack of ease, w[illegible] which the details of the retinal pict[illegible] are discriminated. Unclearness or d[illegible]culty of discrimination from any ca[illegible] whatsoever leads reflexly to musc[illegible] effort towards a corrective readj[illegible]ment which of course in the cases [illegible]der consideration comes to naught [illegible] only induces fatigue. The effec[illegible] color value of light on the power of [illegible] eye to hold itself up to a satisfac[illegible] standard of performance thru a pe[illegible] of work should, we believe, rec[illegible] attention.

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HE SPEED OF ADJUSTMENT OF THE EYE FOR CLEAR SEEING AT DIFFERENT DISTANCES

THE SPEED OF ADJUSTMENT OF THE EYE FOR CLEAR SEEING AT DIFFERENT DISTANCES [1]

A Study of Ocular Functions with Special Reference to Aviation

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By speed of adjustment is meant here speed in the action both of the extrinsic and intrinsic muscles in adjusting for clear seeing at different distances. The amount of lag in this function is found to vary a great deal from individual to individual. In the results to be presented the minimum time required to change from the adjustment for clear seeing at or near the near-point to that for clear seeing at 6 meters, and the converse, has been measured in several cases. So far the investigation has been conducted primarily as a study of the method with special reference to its applicability as a test of fitness for vocations for which speed and accuracy of adjustment are a prerequisite. In this particular especially, the writers believe that the aviator must excel. The rapid development of the science and art of aviation brought about by the present war emphasizes the need for tests which will facilitate the selection of the supernormal eye. It is scarcely to be expected that the conventional clinic tests, designed more particularly for the separation of the subnormal from the normal eye, are fully adequate for this purpose.

It will be obvious without discussion perhaps that in estimating the fitness of an instrument, apparatus, or human organ for a particular task or for the range of work which it may be called upon to perform, other aspects besides maximum power or capacity of response should be taken into account. Some of these are lag, steadiness or stability of response, power to sustain response, rate of fatigue or decay of response, rate of recovery, etc. All of these functional aspects are present in particular in case of the eye and their variation from time to time in a given eye and from eye to eye can be measured with a degree of precision that is adequate at least for many comparative purposes. As

[1] A paper read at the 54th annual convention of the American Ophthalmological Society, July 10th, 1918.

has already been indicated, we have been concerned in the present work with only one of these aspects, namely, the *lag* in the eye's reactions to its stimulus. In the study of this phenomenon at different times in our laboratory, three subdivisions have been made: the lag in the response of the retina to colored and colorless light and its change with change in the intensity of light, the lag in the adjustment of the eye for clear seeing at different distances, and the lag in the development of the perception of depth or distance. The relation of all of these to the functional efficiency of the eye will be considered very briefly in passing.

Because of its small order of magnitude the first of these types of lag is of comparatively little importance in the most of the uses to which the eye is put. In all acts of seeing, for example, in which a change of adjustment is required, the lag in the retina's action is insignificant in amount as compared with the lag in the muscular action. It becomes of importance only in such uses of the eye as permit of a very short exposure to its stimulus, usually with the muscular adjustment already made, or in cases in which it is important to have the maximum response of which the eye is capable. Examples of the former may be found in various uses of the eye in the technical work of the laboratory; and of the latter in signaling with colored and colorless lights. In order to show something of the order of magnitude of the lag in the retina's response and its variation with the wave-length and intensity of light used, we have constructed curves in which the sensation as it rises to its maximum value is plotted in just noticeably different steps against time of exposure. These results were obtained in our laboratory three years ago in a comparative study of methods of determining lag.[2] Four of the most promising of the older methods and three new ones were used in making the determinations; and the results of the several methods were checked against each other. The comparative study was made throughout on the same observers. The dominant motive in making this study was to find or devise a method which would have sureness of principle and precision and at the same time the feasibility that is needed for practical applications. One of the new methods was found to answer surprisingly well to these requirements, considering the nature and difficulty of the problem. The lights employed were narrow bands in the red 686 $\mu\mu$, yellow 588 $\mu\mu$, green 511 $\mu\mu$ and blue 463$\mu\mu$ and white light. The colored lights were taken from the prismatic spectrum of a Nernst filament and the

[2] We are indebted for these results to M. A. Bills, a former graduate student.

white light was synthesized from this spectrum. The lights were all made photometrically equal and in addition, for the sake of more absolute specification, their physical intensities were measured by means of a thermopile.

The results obtained showed that observers differ in all of the following regards: amount of lag for a given stimulus, the amount of difference in the lag for the different wave-lengths and for white light, and the effect on these differences of changing the intensity of light. In case of the observer whose results are given in Fig. I, three intensities of light were used, 0.057, 0.151 and 1.21 meter-candles. It will be noted that for the lowest of these intensities, the rate of rise to the maximum was in the following order: yellow, red, blue, green and white, the time of the maximum ranging between 0.1 and 0.22 sec. For the highest intensity the rates of rise were in the order: Green, yellow, white and red, the time required to reach the maximum ranging between 0.085 and 0.14 sec. Blue was omitted from this series because it could not be obtained at the required photometric value. At the intermediate intensity, a transition condition is shown which can best be gotten from the charts. That is, in passing over a certain range low in the intensity scale to points higher in the scale, there is a radical change in the order of rate of rise tending towards a complete reversal at high intensities; while at intermediate points in the scale, the lag is shown to be in a stage of transition between what is present at low and high intensities. An increase is found also in general to lessen the lag very considerably or to increase the rate of rise. These details, however, are much more important in certain phases of the use of the eye in laboratory technique, for example than they are in immediate relation to the work of the present paper. Our purpose in introducing them here is, as we have already indicated, merely to give some general idea of this feature in the eye's slowness in responding to its task, and in particular to show that as compared with its inertia of adjusting clearly to receive its impression, the inertia in its sensory reaction is relatively unimportant for most of the work which it is called upon to do.

So far our investigation of the lag in the perception of depth has been made in stereoscopic vision, and for an entirely different purpose than the grading of individual capacities. The results show, however, that depth comes into the percept later than height and breadth and color and brightness; and that the amount of lag varies for different observers. Whether this type of lag could be made a feasible basis for the grading of individuals for vocational purposes, we are not prepared

at this time to say. Speed and accuracy in judging distance are doubtless important items in the qualification of an aviator, for example; and it may be possible to work out feasible tests for certain fundamental aspects of the ocular foundation of this ability. Indeed the lag in the adjustment of the eye for clear seeing at different distances should sustain a somewhat fundamental relation to speed of judging distance, since both the adjustment of the eye and the clear seeing of objects are in general the important ocular functions involved in the judgment of distance. Unfortunately for our purpose, however, the judgment itself is not an ocular function. The eye provides only the criteria, and a very complex set of criteria at that, from which the individual learns by experience to form his judgments of distance. The testing of these extra-ocular capacities, the ability to estimate and to learn to estimate distances, more particularly under an entirely new set of conditions for which definite standards or patterns are wanting, is perhaps just as important as the testing of the ocular capacity itself. The testing of the ocular capacity as registered in certain simple space judgments, with or without the element of time or speed of performance, is capable of definite treatment. All that can be said of the remainder of the problem is that it is open to investigation.

On quite a different methodical plane, however, is the determination of the lag in the adjustment of the eye for clear seeing at different distances. The making of these determinations by the method we have used involves no extra-ocular capacities of a higher order than are required in the acuity tests for illiterates. Moreover, a direct objective check is applied to the subjective judgment. That is, the letter E built to scale and turned in different directions is used as a test-object for the different distances; and the observer is required only to indicate the direction in which the letter points in any given case. Such testing of human functions, even without the objective check, is, so far as method and principles of testing are concerned, just as definite as the testing of those physical instruments, whose responses must be read by the eye from a moving pointer and scale or their equivalent.

Our purpose in making these tests has been, as we have already indicated, primarily to ascertain whether eyes rated by the clinic tests as normal or approximately so cannot be more finely graded as to their working efficiency or fitness for special purposes, when other important functions than those considered in the clinic tests are taken into account. For this purpose we have aimed, therefore, to test for the greater part only eyes that have been passed in the clinic as normal, or as

having defects so insignificant as not to need correction. Ninety-four per cent of the eyes of this group were able to read quite readily at 6 meters under 5.2 foot-candles of light the test-type designed to be read at 4 meters; and the remaining 6 per cent, the type designed to be read at 5 meters. In addition a few were tested whose eyes were corrected by glasses. This was done for the purpose of getting results comparative of the performance of eyes corrected to standard according to the norms of the clinic and the uncorrected normal eye. All but one of the uncorrected group were between 18 and 28 years of age and only one of the corrected group was over 28. Three of the observers had worked pretty steadily for a year or more with high power microscopes, four were trained in the observations of physiological optics, and the remainder were selected at random from the college community. The best results were obtained from one of the three who had been trained in the use of a high power microscope; but her results were closely rivaled by those of a college sophomore whose eyes and observational powers had received no special training. However, the results of the three whose eyes had received special training in the use of the high power microscope averaged rather strikingly high. To what extent speed of adjustment can be trained is yet to be determined.

Fortunately for the feasibility of the test, the immediate practice effect is low, or more properly speaking, it is rather high in the initial observations but soon ceases to be troublesome. Also the precision for any given set of determinations is high. As might be expected, though, there is a diurnal variation in the results corresponding to the diurnal changes in the function tested. The maximum range of these variations, however, is small as compared with the range of variation between individuals. It is not great enough, so far as we have thus far been able to determine, seriously to affect the grading of eyes with sufficient precision for practical purposes on the basis of the tests taken at any one time chosen at random. The fact that there is a diurnal variation suggests, however, that if the test be used as a check on fitness for aviation, it might be of advantage to determine each individual's norm and require a short test before each flight, or as often as may be needed to keep track of the variations and to safeguard against the more serious depressions that may occur.[3]

[3] If a check is wanted on the diurnal variations in other motor coordinations as well as those of the eye, a reaction experiment involving choice may readily be combined with the ocular experiment. Two

The working distance for the far object was chosen as 6 meters and for the near object as 18 cm. The far object at this distance subtended a visual angle of 7 min.; the near object, 14.8 min. In choosing both the working distance and the visual angle for the near objects care was taken not to approach too closely to the limiting values. This was needed to safeguard the results against individual differences in the near point and in acuity. That is, it was found that unless these limiting values were too closely approximated, small variations either in the visual angle or the working distance produced little difference in the results.

Since our problem was in part to devise and try out apparatus, the determinations have been made with two types of apparatus, one of which is slightly simpler in construction and use than the other. By means of the more complicated apparatus, however, a more complete analysis of the problem is possible. That is, by means of the simpler apparatus it is possible to make the following determinations: the lag of perception with the eye in approximate adjustment for the near object, the time required to change from this adjustment to that required for far seeing, and the time required for the double excursion, *i. e.*, from near to far and back again to near; while by means of the other apparatus we were in addition able to break up the double excursion into its two halves, the time required to pass from near to far, and back again to near. By means of the second apparatus, moreover, all of the determinations may be made in a single swing of the compound pendulum governing the time of exposure.

forms of this reaction experiment are suggested. (1) A four-finger reaction key may be used, each of the keys to indicate one of the four possible positions of the letters—up, down, right and left. That is, the observer just as soon as each letter,—near, far, and near—is discriminated indicates the direction in which it points by pressing the proper key. (2) A wider range of coordinative ability could be tested by having two keys operated respectively by the right and left hand, and contacts by the right and left foot. By soldering contacts on each edge of the exposure discs in circuit with an electro-magnetic marker and by having the reaction keys and foot contacts also in circuit with electro-magnetic markers, the length of exposure for each test object and the reaction times could all be recorded simultaneously on a kymograph, together with a time line traced by an electric tuning fork. With these records as a check on the quickness of the motor functions of eye, arms and legs and the mental functions involved in choosing, it would seem scarcely possible that the aviator could grow stale or suffer even temporary depressions of any consequence without the knowledge of the laboratory corps. Also from the accumulated records a comparative rating of the stability of the men could be made. It may be, of course, that the eye records alone will serve as a reliable index of the variations in the observer's general condition, but that correlation has not as yet been investigated.

There is another advantage of the second apparatus which came out quite plainly whenever a comparison of results was possible on the same observer. That is, in its use a provision was made to cut off each test object just as soon as it was discriminated. The eye was not allowed to linger on the far object as was its tendency when the double excursion was not broken up into its two halves. The value of the double excursion as determined directly by the first apparatus was, for example, appreciably longer than when it was determined by adding together the values of the two halves as determined by the second apparatus. This tendency of the eye to linger where it can thus not only makes a difference in the absolute value of the results, but there is a danger that it may affect also the comparative values. That is, the latitude offered not only gives a chance for a variable performance or a variable error from time to time with the same observer, but it leaves the results open to the influence of this factor in case of different observers.

Obviously the test may be used in two ways. (1) Records may be made of the maximum performance of each individual. This would be the analogue of making acuity tests in terms of the minimum visual angle each observer is able to discriminate. This procedure is the longer of the two but results in a much finer grading of performance. (2) Two, three, four, or any suitable number of levels of performance may be chosen and the apparatus set at once to give these levels. This method of testing would roughly place individuals into ranks or groups and is the analogue of the Snellen method of grading acuity. It is a much quicker procedure but the grading made is correspondingly rough. By this method the ranking or testing of a given individual by a practiced person should occupy but a few minutes. The results given in this paper were obtained entirely by the former method. It is obvious that the latter method could not be used until sufficient work had been done by the former to establish the required norms for the vocation or purpose in question. Results obtained with the two types of apparatus are shown in Tables I[4] and II.

Since these tables are somewhat detailed, it may be of advantage to give in advance a few points by way of a very general statement of results. The time required for the 18 normal observers to pass from near to far varied between 0.50—1.16 sec., a range of 132 per cent; from far to near, between 0.39—0.82 sec., a range of 110.3 per cent; and from near to far

[4] For the greater part of the results given in Table I we are indebted to M. Almack, a graduate student in our laboratory.

and back to near, from 0.96—1.76 sec., a range of 83.3 per cent. Of these observers, 15 or 83⅓ per cent, required longer to change from near to far than from far to near.[5] If a rough classification by rank were wanted, they might readily be divided into three or more groups with abundance of difference between groups for a graded setting of the apparatus. If, for example, three groups are chosen: fast, medium and slow—fast ranging between 0.95—1.25 sec., medium between 1.25—1.55 sec., and slow between 1.55—1.85 sec., 28 per cent would fall in the first class, 55 per cent in the second class, and 17 per cent in the third class. The observers who wore glasses all grouped together with the slowest of the normal class. The time from near to far for these observers ranged between 0. 89—1.17 sec.; from far to near, between 0.41—0.68 sec.; and the time for the double excursion, between 1.48—1.58 sec. The fastest of this group was 54.2 per cent slower for the round trip than the quickest of the normal group. Under the age of 30, there seems to be no correlation in either group with the age of the observer.[6]

There is a possible bearing of the principles of the test on the work of the clinic which perhaps should not be ignored. That is, in the conventional acuity test accuracy alone is taken into account. No provision is made in the form of the test to include speed of performance. When speed is added to accuracy as a requirement, a degree of sensitivity is given to the test which enables a much finer grading of the resolving power of the eye. For example, two eyes which discriminate detail within the same visual angle can not be said to have the same acuity unless the task can be performed in the same or very nearly the same length of time; yet both might be given the same rating by the conventional test of acuity so far as any safeguarding provision to the contrary is concerned. Indeed when speed is made a feature of the test, differences are readily picked up which would be passed over entirely by the clinic test. Such a refinement of the test need not be especially cumbersome when properly applied to the needs of

[5] The longer time to pass from near to far may, to some extent of course, have been due to the smaller visual angle subtended by the far object. That is, the time required to discriminate the far object may have been increased by its relatively smaller angular value.

[6] So far but few observers have been tested above 30 years of age. The few that have been tested have averaged among the slowest of the normal group. We hope later to make a systematic study of the effect of age on speed of adjustment. In the present study our special purpose has been merely to find out whether individual differences of considerable magnitude are present well below the limit at which the influence of age might reasonably be expected to become effective.

the practitioner, and might, it would be reasonable to suppose, be utilized to advantage as a means of making a more precise diagnosis and in checking up and deciding between corrections, at least in certain difficult and troublesome cases.

From the beginning of our work with short exposures, results were obtained which may have some interest in relation to testing for astigmatism. For example, it was found that in certain cases there was a more favorable meridian for the quick discrimination of the test object. That is, when turned into this meridian a shorter time of exposure was needed to give the judgment required, and small deviations on either side increased the time needed to make the discrimination. In case of the eyes of one of the writers (Ferree), for example, a difference in result amounting to 40 per cent was found for this meridian and the meridian at right angles to it. A deviation of 5 degrees either way from this most favorable meridian gave a difference in result amounting to 16 per cent. The astigmatism was so slight that it could not be detected on the astigmatic chart. It was located by means of the ophthalmometer. A +.12 cylinder served to make the time record equal for the two meridians and to eliminate the astigmatic showing by the ophthalmometer. On further study of several cases the test was shown to possess a pronounced sensitivity to astigmatism even without any additional or special modification better to meet the requirements of that particular application.[7] Some of the results of this study are shown in Table III.

The requirements of the apparatus needed to make the foregoing determinations are comparatively simple. Some means must be provided for giving the exposures to the near and far test objects which will immediately succeed each other in the required order and which can be varied by very small amounts and be repeated with precision. The first of the above requirements can best be met by making the successive exposures all a part of the same system of motion. The simplest way in which all of the requirements mentioned can be satisfied is perhaps to have the exposures made by means of a set of lightweight discs of variable open and closed sectors turned by means of a bar fastened at its center to the axle to which the

[7] Before the lag records are made it is recommended, of course, that astigmatisms be corrected. However, even if they are not corrected low astigmatisms will give little trouble unless the defect is in the same meridian in both eyes. There will then be more and less favorable meridians for the quick discrimination of the test object. The difficulty can be overcome fairly well, however, and the record be made without serious injustice to the ranking of the observer by avoiding turning the test object into the most and least favorable meridians.

discs are attached and provided with adjustable weights on both arms. Such a system operates as a compound pendulum and has all of the characteristics and constancy of motion of a compound pendulum. The length of exposure can be varied either by changing the width of the open sector or the position of the weights on the arms. By utilizing both of these variables to their fullest extent, changes can readily be made of the order of thousandths of a second or even less, and a total range of exposure can be given varying from these values up to several seconds. Most of our work was done, for example, by one adjustment of the position of the weights on the arms, giving a slow rate of turning. Constancy of rate of turning and therefore constancy of length of exposure with a given value of open sector and a given position of weights on the bar was secured by always releasing the bar at the same point in the arc through which it makes its swing. On the back of each set of discs is a protractor or graduated circle by means of which the values of the open sectors can be read to degrees or fractions of degrees. These values in degrees for any number of observers or observations, if the discs are made of sufficiently light material, can be converted into units of time by a single process of calibration which will be described later.

In Fig. II is shown the first or simpler apparatus. The exposure discs A, B, C and D are cut from hard sheet aluminum, No. 20 B & S gauge. Each of these discs are cut as shown at X in the figure, the inner portion, radius 6.5 cm., solid; the outer portion open to a value of 172°. The breadth of this outer zone for discs A and B is 14.5 cm.; and for discs C and D, 22.5 cm. The difference in the breadth of these two sets of discs has to be such that the smaller will just cover one of the near test objects, and the larger, the other, the two objects being placed far enough apart in the same vertical plane to permit of a clear view between them with either eye of the far object. All of these discs are attached to an axle to the end of which is fastened the bar, 2½ meters long, which carries the weights, M and N, which serve as the driving power of the apparatus. These weights are of equal mass, therefore the moment of turning of the system is governed, roughly speaking, by two factors; the combined distance of the two weights from the center of rotation, and the difference in the distance of the weights from that point, provided, as already stated, the swing is always begun at the same place in the arc through which the system turns. To give stability of support the axle turns in bearings at the ends of the two arms of a heavy Y-shaped support. A clutch, adjustable in

height, supports the bar before it is released for its swing and guarantees that it always starts from the same position. The discs A and C are pinned permanently to the axle in such a position that when the bar is held in the clutch, A just covers one of the test objects and C the other. The discs B and D are free to turn about the axle and when adjusted for a given value of exposure are clamped in position by means of a nut and washer. Immediately in front of these discs are the two octagonal cards at the center of each edge of which is printed one of the test letters. These E's are so turned that by rotating the card the letters can be presented all precisely at the same place, pointing up, down, right, left, and the four corresponding 45° positions in any order that may be chosen. The card itself is mounted at its center on a small metal disc at the end of a grooved pin 6.5 cm. long. This pin passes through a collar provided with a set screw which feature permits of a certain latitude of adjustment of the distance of the test card from the exposure discs. To provide for the rotation of the test card this collar turns in a sleeve supported by a grooved carrier. This carrier slides on a track, to permit of the needed latitude of adjustment of the test object to right and left. The far test object is printed on a larger circular card which is mounted at its center on a small metal disc at the end of a pin which passes through a broad collar permitting of its free rotation. At the other end of this pin is a pulley so arranged that by means of two cords which thread through a guide ring 21 cm. below the center of the pulley, the card can be rotated to any position desired by the experimenter stationed at the exposure apparatus. The circumference of this card which turns immediately behind a pointer is graduated in degrees to indicate the meridian into which the test letter is turned. Between the observer and the exposure discs, as near to these discs as possible, is a cardboard screen with an aperture of such a height and breadth as to give a clear view of the near and far test object with either eye and to cut off the rest of the field of view and the moving discs.

The near test cards were illuminated by diffuse light reflected from the mat surface of the back of the cardboard screen between the observer and the exposure discs. The light was supplied by a tubular tungsten lamp enclosed in a cylindrical housing provided with a vertical aperture of a suitable breadth. This housing can be rotated about the lamp to give the proper angle of incidence of the light on the reflecting screen. The far test object was illuminated by a tungsten lamp mounted in an X-Ray deep bowl reflector so

directed as to give an even illumination of the test surface and to shield the eye from glare. All of the test objects were brought as nearly as possible to a brightness and color match at a brightness value of 0.007 candlepower per square inch. The value of the illumination at the test object was 5.2 foot-candles. The general illumination of the room was indirect with an average value of 2.89 foot-candles, vertical component; 1.11 foot-candles, horizontal component; and 2.64 foot-candles, 45° component.

The experimental procedure was as follows. The three test objects and the eyes of the observer were adjusted to the same vertical level, and the two near objects were separated far enough to give the observer a clear view of the far object with either eye. Discs A and B were adjusted so as just to permit of the discrimination of the near object immediately in front of them; and C and D, the discrimination of the far object in case the time to pass from near to far is wanted, and of both the far object and the remaining near object in case the time of the double excursion is desired. In making each determination three correct judgments out of a possible five were required. A preparatory adjustment of the observer's eye was secured by having him fixate a point on the discs in line with the near object first exposed and 3 mm. nearer to the eye. In order that the preparatory interval be as favorable as possible, the observer was required to give the signal for the release of the pendulum.

It should be noted in passing perhaps that the adjustment of the discs A and B is not made entirely or even primarily for determining the lag in perception with the eye in approximate adjustment for the near object, although that is an item that might be of value perhaps in our comparative study of the lag of the ocular functions of different individuals. It has been made chiefly in order that the determination of the time to pass from near to far and back again to near shall be made with greater precision. That is, it is obvious that if the observer is to begin his excursion from near to far with an exact adjustment for clear seeing at near, it must be required as a check that he start with a task which involves a report of clear seeing at near. The mere instruction to fixate a point, for example, will not guarantee the needed adjustment. Moreover, it is equally obvious that the adjustment must be precisely controlled if the results are to be safeguarded against the variable error that has already been discussed with reference to the exposure of the far object. That is, if it is not controlled, the eye may linger too long at near or begin too soon its change towards far, and the amount of deviation in either

regard may vary from time to time and from individual to individual.

In the second type of apparatus (Fig. III) our purpose, it will be remembered, was to make it possible to do all that could be accomplished with the first apparatus, and in addition to provide for the separate determination of the time required to pass from near to far, and back again to near in a single swing of the pendulum. In order to do this it was necessary to have behind the near test objects a second set of discs attached to the same axle, one of the sectors of which when properly adjusted cuts off the far object as soon as it is discriminated. That is, in this apparatus, the aperture of the two smaller sectors, A and B, of the nearer set of discs gives the time of perception of the near object on the observer's left; the aperture between B of this set and F of the farther set gives the time needed to pass from near to far; and the aperture between this disc and the disc D of the nearer set the time required to pass from far back again to near. The other discs, E of the far set and C of the near set, are pinned permanently to the axle and are rigidly connected, with the edge of each at exactly the same level. Both sets of discs are provided with graduated circles. At the edge of each of the moveable sectors are pointers for reading the values of the open sectors. As the apparatus now stands, the two sets of discs are both between the Y-shaped support and the observer and are only 10 cm. apart. Since the graduated circles are on the back of each set of discs, this makes the reading of the circle on the near set somewhat inconvenient. In a new apparatus now in construction, the near set will be attached between the observer and the support in which the axle turns, and the far set beyond this support. This provision will give ample space between the two sets of discs for the convenient reading of the scale on the near discs.[8]

[8] Also in the newer form of apparatus the near test cards are illuminated by a tubular tungsten lamp installed in the horizontal in a plane midway between the screen and the near test objects, so that the center of its filament is about 12 cm. above the two test objects and equidistant from them. The test objects thus receive their light in part directly from the lamp and in part by reflection from the screen. In this way it is possible to make the intensity of light received by the two objects more nearly the same than is the case with the illuminating device shown in Figs. III and IV. On the platform between the two sets of discs is installed a second lamp, suitably shaded, which can be turned on and off at will for the reading of the graduated circle on the back of the set of discs nearest the observer. (Since the above paper was presented this newer type of apparatus has been taken overseas for the purpose of studying and checking up the diurnal variations in the ocular condition of the aviators on the western front.)

With both types of apparatus, all readings are made in terms of degrees of open sector. These readings can after any number of sets of observations be converted into units of time by a simple process of calibration. Smoked paper is clipped to the disc across the open sector; the pendulum is released with the weights, the starting point, etc. just as they were in the original determinations; and a time line is run across the open sector by means of an electric tuning fork whose vibration frequency is known. The paper can be removed, shellacked and counted at leisure. In counting, the given degree values can be laid off on the shellacked record by means of another protractor. If the discs are made of material so light that the different positions of the moveable discs do not change by significant amounts the relative accelerations of the pendulum at the different points in its path,[9] a calibrating chart may be made once for all for the full range or any range of open sector that may be desired. Another method which we have used is to have contacts soldered to the edges of the sector, in circuit with an electro-magnetic marker writing on the smoked paper of a kymograph. Because of a certain amount of lag in this system of recording, the method was abandoned in favor of the one described. In practical use, however, where an exact quantitative rating of performance is not required, there is no particular need of converting the readings on the scale into units of time. This is especially true if the apparatus is used, as is the Snellen method of rating acuities, merely to classify performance roughly by the rank method. That is, in this case it is set to give in turn the different levels of performance chosen, and the eye is rated by the highest level which it is able to attain.

[9] Light cardboard, for example, could be used, if desired, for these discs instead of aluminum.

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SHOWING THE INERTIA OF ADJUSTMENT O
Observers wi

Observer	Age	Degree values: Near object	Degree values: Near to far	Degree values: Near to far and back to near	Time values (sec.): Near object	Time values (sec.): Near to far	Time values (sec.): Near to far and back to near	Ind De Near to f: Seconds	P
Sl.........	25	1	31	64	0.02	0.50	0.96		
Fl.........	26	1	42	73	0.02	0.68	1.05	0.18	
St.........	23	1	38	85	0.02	0.64	1.17	0.14	
C..........	25	1	44	103	0.02	0.72	1.37	0.22	
Mc........	27	1	53	105	0.02	0.77	1.41	0.27	
Ln.........	26	1	39	105	0.02	0.65	1.41	0.15	
F..........	40	2	54	124	0.04	0.775	1.85*	0.275	

* Compare this result with that obtained with the same observer with Apparatus II. It the first apparatus than with the second in all cases in which the determinations were made to cut it off just as soon as it was discriminated.

for Clear Seeing at Different Distances
eyes. Apparatus I

ences quickest		Supplementary data			
ear to far and back to near onds	Per cent	Acuity	Near point (cm.)	Refraction	Muscles
		O.D.:6/4	11.5	Emmetropic	1 Exo.
		O.S.:6/4	12.5	+.12 cyl. ax. 90°.	
.09	9.4	O.D.:6/4	12.5	+.50 S.+.25 cyl. ax. 180°.	2 2/3 Eso, 1/3 LH
		O.S.:6/4	12.5	+.62 S.	
.21	21.9	O.D.:6/4	10.4	+.25 S. + .25 cyl. ax. 75°	2 1/2 Eso, 1 R H
		O.S.:6/4	10.4	+.25 S. + .12 cyl. ax. 90°	
.41	42.7	O.D.:6/4	11.3	—.25 cyl. ax. 80°	2 Exo, 1 RH
		O.S.:6/4	11.3	—.12 cyl. ax. 95°	
.45	46.9	O.D.:6/4	12.5	Emmetropic	1 Eso
		O.S.:6/4	12.5	Emmetropic	
45	46.9	O.D.:6/4	11.5	+.25 S.	1 1/4 Eso, 1 RH
		O.S.:6/5	10.5	—.25 S.	
89	92.7	O.D.:6/4	15.0	+.12 cyl ax. 120°.	3 Eso
		O.S.:6/4	15.0	+.12 cyl. ax. 15°	

bered that we have stated (p. 46), that a longer time was required for the double excursion with
bserver, owing to the tendency of the eye to linger on the far object when no provision was made

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SHOWING THE INERTIA OF ADJUSTMENT O
Observers w

Observer	Age	Degree values* Near object	Near to far	Far to near	Near to far and back to near	Time values (seconds) Near object	Near to far	Far to near	Near to far and back to near	Individu Near t Seconds
H............	19	1	48	44	92	0.02	0.63	0.39	1.02	
Lz............	25	1	56	48	104	0.02	0.75	0.42	1.17	0.12
Bk............	25	1	59	55	114	0.02	0.77	0.47	1.24	0.14
L............	19	2	59	64	123	0.04	0.76	0.565	1.325	0.13
Rg............	28	1	55	70	125	0.02	0.715	0.61	1.325	0.085
Ty............	24	1	55	87	142	0.02	0.69	0.76	1.45	0.06
D............	22	1	51	63	114*	0.02	0.825	0.675	1.50	0.195
S............	24	2	68	75	143	0.045	0.85	0.66	1.51	0.22
F............	40	1	64	81	145	0.02	0.79	0.73	1.52	0.16
B............	19	1	57	92	149	0.02	0.705	0.82	1.525	0.075
M............	18	1	79	70	149	0.02	0.94	0.635	1.575	0.31
Rs............	24	2	98	60	158*	0.06	1.16	0.60	1.76	0.53
With glasses,—Apparatus II.										
W............	25	3	77	42	119*	0.09	1.02	0.46	1.48	0.39
Bt............	27	2	63	75	138*	0.04	0.89	0.68	1.57	0.26
R............	31	1	105	43	148	0.02	1.17	0.405	1.575	0.54
Hk............	27	1	82	62	144	0.02	1.015	0.565	1.58	0.385

* In the four cases marked with an asterisk, longer exposures were needed than could be
exposure needed was secured by changing the positions of the weights on the bar.

FOR CLEAR SEEING AT DIFFERENT DISTANCES
eyes,—Apparatus II

:es: Deviation from quickest						Supplementary data	
Far) near ids	Percent	Near to far and back to near Seconds	Percent	Acuity	Near point (cm.)	Refraction	Muscles
				O.D.:6/4	10.3	Emmetropic	1 1/2Eso.
				O.S.:6/4	10.3	Emmetropic	Add:Abd+20:9
3	7.7	0.15	14.7	O.D.:5/4	12.5	—.12 cyl. ax. 180°	3 Eso, 1 RH
				O.S.:6/4	13.0	Emmetropic	Add: Abd=26:5
8	20.5	0.22	21.6	O.D.:6/4	13.0	+.12 cyl. ax. 60°	1/3 RH
				O.S.:6/4	12.5	+.12 cyl. ax. 120°	Add: Abd=22:11
75	44.9	0.305	29.9	O.D.:6/4	11.0	Emmetropic	1 Exo
				O.S.:6/4	8.6	—.25 cyl. ax. 5°	Add: Abd=10:8
2	56.4	0.305	29.9	O.D.:6/4—	12.0	—.12 cyl. ax. 122 1/2°	1 1/4 Eso
				O.S.:6/4—	13.0	Emmetropic	
7	94.9	0.43	42.2	O.D.:6/4	12.0	Emmetropic	1 Exo
				O.S.:6/4	10.5	Emmetropic	Add: Abd=22:7
35	73.1	0.48	47.1	O.D.:6/4	9.5	—.12 cyl. ax. 157 1/2°	3/4 Eso
				O.S.:6/4	9.5	—.25 cyl. ax. 17°	Add: Abd=18:5
	69.2	0.49	48.0	O.D.:6/5+	10.5	—.25 S.	1 Eso
				O.S.:6/4	11.0	Emmetropic	Add: Abd=14:8
	87.2	0.50	49.0	O.D.:6/4	15.0	—.12 cyl. ax. 120°	3 Eso
				O.S.:6/4	15.0	—.12 cyl. ax. 15°	Add: Abd=12:3 3/4
	110.3	0.505	49.5	O.D.:6/4	9.0	—.25 cyl. ax. 150°	1 Eso, 1 1/8 RH
				O.S.:6/4	11.0	—.25 cyl. ax. 5°	Add: Abd=20:10
5	62.8	0.555	54.4	O.D.:6/4	8.0	Emmetropic	1 Exo
				O.S.:6/4	8.0	Emmetropic	
	53.8	0.74	72.5	O.D :6/4	9.0	Emmetropic	4 LH
				O.S.:6/4	10.5	—.25 cyl. ax. 90°	Add: Abd=14:9
				With glasses,—Apparatus II			
	17.9	0.46	45.1	O.D.:6/6	12.0	+.25 cyl. ax. 180°	1 1/2 Eso
				O.S.:6/15	12.5	+.50 cyl. ax. 115°	Add: Abd=20:9
	74.4	0.55	53.9	O.D.:6/5+	9.5	—3 S.—1.37 cyl. ax. 15°	Ortho
				O.S.:6/5+	10.5	—3 S.—1.37 cyl. ax. 165°	Add: Abd=20:9
	3.8	0.555	54.4	O.D.:6/4	9.0	—1 S.—.37 cyl. ax. 150°	1/4 Exo, 1/2 RH
				O.S.:6/4	10.0	—.25 S.—.25 cyl. ax. 180°	Add: Abd=24:8
	44.9	0.56	54.9	O.D.:6/4—	11.0	—.50 S.—.25 cyl. ax. 120°	3/4 Eso, 1/2RH
				O.S.:6/5+	10.5	—.87 S.—.37 cyl. ax. 60°	Add: Abd=21:9

ging the setting of the discs with a given position of the weights on the bar. The range of

TABLE III

Showing a comparison of the time required to discriminate the far object in the most favorable meri[illegible] and the meridian 90 degrees from this in cases of low astigmatism,—also the difference in the time required for the most favorable meridian and for meridians 5 degrees on either side

Observer	Refraction	Time of discrimination of far object in seconds: Most favorable meridian	At 90° from most favorable meridian	Difference for two meridians: Seconds	Per cent	Difference prod[illegible] by a change o[illegible] in either direc[illegible]: Seconds	Per [illegible]
R(O.S.)...	—.25 cyl. ax. 5°	0.70	0.95	0.25	35.71	0.09	[illegible]
R(O.D)...	—.37 cyl. ax. 150°	0.96	1.40	0.44	45.83		
F.........	+.12 cyl. ax. 120°	0.80	1.12	0.32	40.00	0.14	[illegible]
B.........	—.25 cyl. ax. 150°	0.65	1.02	0.37	56.92	0.06	[illegible]
T.........	—1.25 cyl. ax. 170°	0.55	0.84	0.29	52.73	0.12	[illegible]
L.........	—.25 cyl. ax. 5°	0.76	0.88	0.12	15.79		

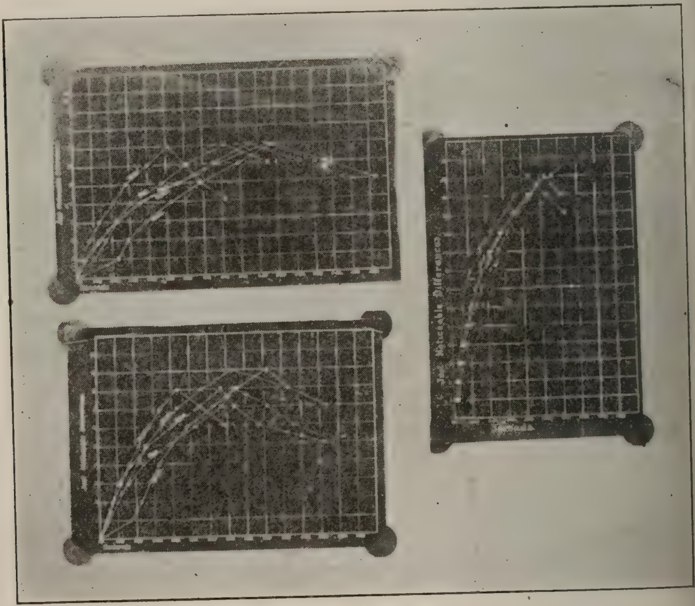

FIG. I

Showing the results of a determination of the lag in visual sensatio[n] in its relation to wave-length and intensity of light. In A (upper left) the lights employed were made photometrically equal to 0.057 meter-candles; in B (lower left), at 0.151 meter-candles; and in C (right) at 1.21 meter-candles.

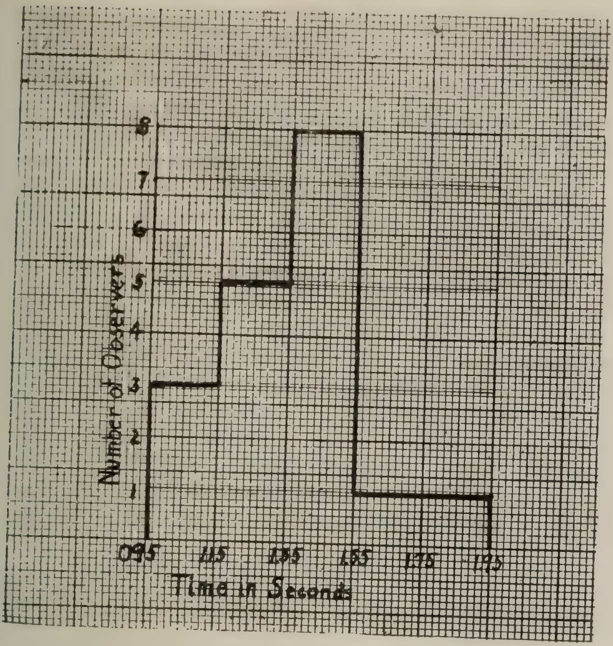

FIG. II

Representing the relative distribution of 18 observers graded with reference to speed of adjustment for clear seeing at different distances.

Once a feasible method and apparatus are had for determining the speed and accuracy with which the eye may be adjusted for clear seeing at different distances a number of problems are open for investigation. As already indicated two of the points which we hope to study in the near future are diurnal variations and the slowing effect of age. The latter of these points becomes of importance if men of the age of the late Mayor Mitchell are to enter aviation and other vocations for which speed and accuracy of ocular adjustments are a prerequisite. The results which we have obtained thus far on older subjects (not included in the preceding tables) suggest that above the ige of 30, the eye becomes not only slower in its reactions but ncreasingly liable to lapses and depressions lasting through onger or shorter intervals of time which make it a tardy and inreliable instrument for much of the work it is called upon o do, more particularly for the special vocations requiring peed of performance. That such lapses are a menace to the

aviator is now pretty generally recognized. It is a matter of common report that even the young aviator under the strain of the prolonged performance of his task grows stale. If so, it is obvious that a careful check should be kept on the sensory and motor foundations of his fitness for his work. In this procedure the speed of reaction of his skeletal as well as his ocular muscles doubtless should be included (cf. foot-note p. 44). By adding these supplementary reactions to the test a broader basis would be laid for keeping track of the variations in the aviator's ability to see his objects quickly and to perform the reactions needed for the control of his machine. In calling attention to these subsidiary questions, however, we do not wish to obscure what we believe to be the most promising application of the test, namely the initial grading of men as to fitness for work requiring special ocular capacities.

The apparatus described is now being used in France for the study of the diurnal variations in the aviator's ocular fitness for his work. It is also being used by the Ophthalmological Division at the Medical Research Laboratory at Mineola. Among the problems in prospect there the following three may

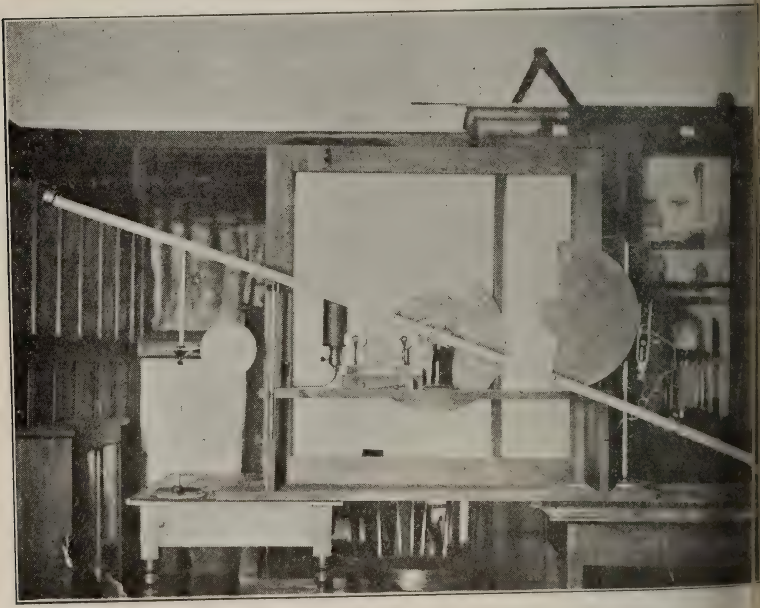

Fig. III

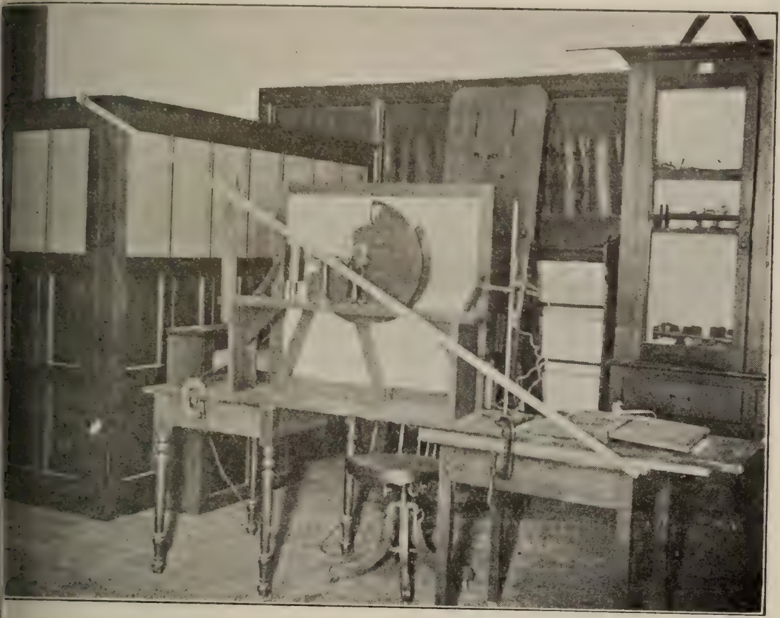

FIG. IV

be noted: (1) the standardization of the test for the selection of aviators, (2) a study of the diurnal variations in the aviator's ocular fitness for his work, and (3) a study of the ocular effects of oxygen poverty.

[Reprinted from the PSYCHOLOGICAL BULLETIN, Deeember, 1918, Vol. 15, No. 12.]

A NOTE ON VISION—GENERAL PHENOMENA

We wish to make the following corrections of Dr. Troland's review of work published by us during the year 1917–1918.

1. He says of our work on "The Power of the Eye to Sustain Clear Seeing under Different Conditions of Lighting": "Semi-indirect reflectors of high density seem to be most conducive to eye comfort." While this conclusion would perhaps be more agreeable and satisfactory to certain commercial and professional factions in lighting circles, it was not drawn by us nor can it be drawn from our results. Of the commercial reflectors tested by us thus far, unmodified by any experimental device for the improvement of their effect on the eye (cf. Opaque Direct Reflectors, *Trans. of Illum. Eng. Soc.*, 1917, **12**, pp. 466–468), the best results have without question been obtained with the totally indirect reflectors.

2. Of our article, "Some Areas of Color Blindness of an Unusual Type in the Peripheral Retina," he says: "Ferree and Rand report observations which show that areas can be found in the peripheral visual fields of many persons which are relatively blind to red, green, yellow or blue but which are not correspondingly deficient in the complementary after-image and other related reactions." There is no ground for using the term "relatively blind" here. It was shown in the article reviewed that stimuli so intense as to carry the sensitivity to red, yellow and blue out to the limits of white light vision were not sensed as color in these areas. Further in order to leave no doubt as to their color blindness the series was made to include also stimuli so intense as to give colors greatly reduced in saturation when viewed in central vision. If areas so tested are to be called "relatively blind" it is difficult to understand why the term color blind should ever be used. What we actually reported was that both types of areas, color blind and color deficient, showing no detectable loss in the cancelling and after-image functions were to be found in the peripheral retina.

3. Our discussion of the "Needs and Uses of Energy Measurements in Psychological Optics" is represented in a way which we do not care to have stand uncorrected in the year's reviews of work. Our argument was that if we are to determine the sensitivity of the eye in a way that is comparable with the determination of the sensitivity of the physical recording instruments we should be able to compare numerically both our amounts of response and

amounts of stimulus. The question whether st muli should be equated subjectively or in energy terms for investigations bearing on various points of theory or doctrinal conception was quite aside from the main purpose of the paper. Which type of equation should be used depends on the nature of the problem in hand, as was made clear as a feature of minor importance in the article reviewed. The need of a method logically sure for the determination of sensitivity was the particular point of emphasis and it was with reference to this point especially, which we believe is at present the most important in the laying of the groundwork of a more scientific psychophysics of vision, that our recommendation of energy measurements was made. In this connection it may be noted further that the article reviewed is in part a criticism of the reviewer's own advice that the eye may be used as a substitute for the nonselective instruments in the measurement of light energy; and that our criticism of this recommendation was not by any means based alone on the inadequacy of the "extant visibility data." These points are discussed in greater detail in two articles (Titchener Commemorative Volume, pp. 230–308 and *Psychological Monographs*, No. 103) which were not reviewed by Dr. Troland.

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CHROMATIC THRESHOLDS OF SENSATION FROM CENTER TO PERIPHERY OF THE RETINA AND THEIR BEARING ON COLOR THEORY

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CHROMATIC THRESHOLDS OF SENSATION FROM CENTER TO PERIPHERY OF THE RETINA AND THEIR BEARING ON COLOR THEORY

PART I.

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INTRODUCTION

In the work reported in this paper a determination of the chromatic thresholds of red, green, blue and yellow in energy terms has been made at near-lying points from the center to the periphery of the retina. The incentive for making this study has been twofold: (1) We have wanted to make an investigation of the chromatic sensitivities of the central and peripheral retina that would be more nearly quantitative than those that have previously been attempted. (2) A detailed investigation of the sensitivity gradient for the four colors red, green, blue, and yellow from center to periphery of the retina has an important bearing on certain points of color theory. Two of these points will be considered in the second part of this paper.

As a part of a general investigation of retinal sensitivities we had planned several years ago (1) to make determinations both of the achromatic and chromatic sensitivities to wave-length that would be quantitative up to the standard accepted for the physical recording instruments. One of the requirements for such a determination is, as was pointed out at that time, that the stimuli shall be rated in units that can be compared. This requirement could not be met until measuring instruments were obtained which were sufficiently senstitive for work in the visible spectrum and which were non-selective in their response to wave-length. It was further stated that if a rating is to be made which may fairly be considered as quantitative, it must also be possible from the

data at hand to compare numerically the amounts of response as well as the amounts of stimuli used to arouse the response. That is, while a radiometric rating of the stimuli is necessary for this purpose, an equally important point to be considered is what amounts of response can be employed with sureness of principle in meeting the quantitative requirement. In this regard it was pointed out that of the amounts of response that have at different times been used or suggested for the determination of sensitivity—namely, equal amounts, equal sense differences, the liminal threshold, the just noticeable difference, and the average error—perhaps only the first two can by common agreement be regarded as numerically comparable; and that the validity of the use of the others for the more strictly quantitative work should be tested by checking the results against those obtained when the rating is based, for example, on equal amounts taken as standard. This interchecking of results for achromatic sensitivity is now in progress in our laboratory, in which case all of the determinations mentioned above may be made. It can not be done, however, in case of chromatic sensitivity until it is first determined whether the judgment of equal saturations can be made with an acceptable degree of precision. Furthermore, a determination of comparative sensitivities in the peripheral retina, based on equal amounts of response, while not impossible, is neither very convenient nor very feasible. For the purpose of the present paper, therefore, we have been content to deal with the determination of the chromatic threshold for the wave-lengths in question and of their variation from the center to the periphery of the retina, which work has an interest of its own independent of its bearing on a determination of comparative sensitivities, and to reserve a report on the more strictly quantitative features of the general problem for a later paper. In making these determinations it was our intention to work at nearing points from the center to the periphery of the retina in several meridians. The work was interrupted, however, by the pressure of other investigations when the determinations had been made in only two meridians, the temporal and the

nasal. Results can be given at this time, therefore, for only these two meridians.

Conditions under Which the Work was Done

The determinations were made under the following conditions. (1) The colored lights used were taken from the spectrum. There are two reasons for this in an investigation of the kind here undertaken. (*a*) The stimuli should be as homogeneous with regard to the visible wave-lengths as possible,[1] and (*b*) they should be free from the infra-red and ultra-violet radiations which would affect the thermopile used to measure the intensity of light, but not the eye. The stimuli employed were a narrow band of red in the region of 670 $\mu\mu$; of yellow in the region of 581 $\mu\mu$; of green in the region of 522 $\mu\mu$; and of blue in the region of 468 $\mu\mu$. The breadth of analyzing slit used in isolating these bands was maintained constant at 0.5 mm. The range of wave-lengths obtained was approximately 660–680 $\mu\mu$; 575–587 $\mu\mu$; 518–526 $\mu\mu$; and 468–474 $\mu\mu$. The spectrum was gotten and the different wave-lengths were presented to the eye by means of the apparatus described in the *Journal of Experimental Psychology*, 1916, 1, pp. 247–284: 'A Spectroscopic Apparatus for the Investigation of the Color Sensitivity of the Retina, Central and Peripheral.' In every case the light was examined for impurities at the analyzing slit by means of a small Hilger direct vision spectroscope provided with an illuminated scale. When found, impurities were absorbed out by thin gelatines selected so as to cut out as little of the useful light as pos-

[1] The presence of the alien visible wave-lengths affects the results of a determination of chromatic sensitivity in two ways: (*a*) through physiological inhibitions and interactions it decreases the amount of the color response, and (*b*) it increases the energy measurement. In their work on the determination of the visibility of radiation in the red end of the visible spectrum, Hyde and Forsythe (*Astrophysical Journal*, 1915, 44, p. 289) found impurities in the prismatic spectrum to the value of about 20 per cent., at 0.76 μ. In our own work both on achromatic and chromatic sensitivity determinations made with and without provisions for absorbing the scattered light, show differences in result which are great enough to be considered of significance. This is true in particular for determinations of chromatic sensitivity, in which case the chromatic response may be reduced quite appreciably as a result of the physiological interactions produced by the alien wave-lengths. In some cases, for example, even the complementary wave-lengths may be present.

sible. These gelatines were placed over the analyzing slit and were held in position by short clips fastened to the front surface of the jaws the edges of which formed the slit.

(2) The determinations of the threshold were made in energy terms. Measurements were made at two places: at the analyzing slit and at the eye. In making the threshold determinations of the stimulus light it was found to be convenient first to make the colors all equal in energy value. The reductions needed for the equalization were made by appropriate adjustments of the collimator slit. Since the blue represents the smallest amount of energy of any of the colors employed, they were all made equal in energy to the blue of the spectrum used, namely, the prismatic spectrum of a Nernst filament operated by 0.6 ampere of current. From this intensity they were reduced to the threshold by means of the especially constructed sectored discs described in an earlier paper,[1] and the energy values computed from the simple law of the disc. These discs, it will be remembered, were cut from hard sheet aluminum, No. 20 B. and S. gauge, 0.9 mm. thick, and of two sizes for just noticeable difference determinations, 19.5 and 17 cm. in radius. The total variation of range of open aperture is from 0° to 348.75°. A strong objection to the use of sectored discs when fine changes are needed such as are required, for example, in threshold and just noticeable difference work, is the difficulty of obtaining and measuring accurately sufficiently small amounts of change. Such discs are ordinarily constructed with two or more open sectors and a change in one is multiplied as many times as there are open sectors. Moreover, an error made in the measurement of one sector is multiplied by the number of open sectors. This latter difficulty becomes especially significant in working with intensities at or near the threshold, where a small error may represent a high percentage of the total open sector. We have sought to overcome these difficulties in three ways. (1) Our discs for a low total aperture are so constructed that one sector may be varied at a time. (2) The sector is moved by

[1] *Journal of Experimental Psychology*, 1916, 1, pp. 271–274.

means of a micrometer screw. This device for minute changes in the value of the open sector is so constructed as to be readily attached and removed from the disc. And (3) a special protractor has been designed fitted with a movable arm carrying a knife edge and Vernier scale graduated to read to minutes. Obviously some such precise means of making and measuring small changes in the disc are of prime importance in the work of determining the threshold and just noticeable difference. If such means are not at hand the average error of setting and measurement is apt to exceed that of the sense judgment.

The method of making the energy measurements by means of a thermopile has already been described in a previous paper. However, because the procedure is as yet somewhat unfamiliar it may not be out of place to give again brief description of how the measurements are made. A description at one of the places at which they were made, namely the analyzing slit, will be sufficient to show in a general way the method we have employed. The thermopile to be used was placed in position immediately behind the slit and a blackened aluminum shutter was interposed in the path of the beam of light between the slit and the end of the objective tube of the spectroscope. Preliminary to the exposure of the thermopile to the light to be measured, the current sensitivity of the galvanometer was tested by means of a special device[1] provided for this purpose in the construction of the galvanometer. With regard to this procedure it may be pointed out that the current sensitivity of the galvanometer varies with the period or time of the single swing of its needle system. Since it is not possible to control the field so as to get this period always the same, it is necessary, if results are to be compared, to take some sensitivity as standard and to convert all readings into deflections for the standard sensitivity by means of a correction factor determined at each sitting. For a detailed description of the method of de

[1] This device consists of a special galvanometer coil, dry battery circuit, and switchboard with finely graduated resistance. For a description of this device, see 'Radiometric Apparatus for Use in Psychological and Physiological Optics,' Psychol. Rev. Monog., 1917, 24, No. 2, pp. 63–65.

termining this factor, see PSYCHOL. REV. MONOG., 1917, **24**, No. 2, pp. 60–65.

The thermopile was next connected with the galvanometer and the light allowed to fall on its receiving surface until a temperature equilibrium was reached (ca. 3 sec. for our thermopile). The deflections were read by means of the telescope and scale and the readings are corrected to standard sensitivity by means of the factor previously determined. The final step in the process of measuring was the calibration of the apparatus, *i. e.*, the value of 1 mm. of deflection in radiometric units was determined for the area of thermopile exposed. To do this a radiation standard, the value of the radiations from which is already known, had to be employed. The standard used by us was a carbon lamp specially seasoned and prepared for the purpose by W. W. Coblentz (4) of the radiometric division of the Bureau of Standards. This lamp was placed on a photometer bar 2 meters from the thermopile and operated at one of the intensities for which the calibration was made, in our case 0.40 ampere. The thermopile was exposed to its radiations with the same area of receiving surface as was used in case of the lights measured, and the galvanometer deflection was recorded. From the deflections obtained the value of 1 mm. of deflection, or the radiation sensitivity of the apparatus under the conditions given, was computed from the known amount falling on the surface of the thermopile. Having the factor expressing the radiation sensitivity of the apparatus, the deflections produced by the wave-lengths of light measured were readily converted into energy units. The radiation sensitivity of the linear thermopile used by us was computed in a given case, for example, from the following data. The energy value of the radiations per sq. mm. at a distance of 2 m. from the standard lamp operated by 0.40 ampere was 90.70×10^{-8} watt. The deflections of the galvanometer produced by this intensity of radiation falling on the same area of receiving surface as was used in measuring the lights employed as stimuli, when corrected (*a*) to a sensitivity of $i = 1 \times 10^{-10}$ ampere, and (*b*) for the absorption of the glass cover of the thermo-

pile, was 346.870 mm. The area of the surface exposed was 4.400 sq. mm., and the time of exposure was 3 sec. The sensitivity of the instrument per sq. mm. of receiving surface was, therefore, 115×10^{-10} watt. By means of this factor the galvanometer readings produced by the different wave-lengths of light may readily be converted into the energy value of light falling on the receiving surface of the thermopile.

(3) The field surrounding the stimulus, and the preëxposure were always maintained as nearly as possible at the same brightness as the stimulus at the threshold value of sensation. For want of better pigment materials these surfaces were made from the Hering standard gray papers. It was found to be necessary to change the brightness of the surrounding field and preëxposure frequently for each stimulus because the brightness value of the color at the chromatic threshold changed quite rapidly from the center to the periphery of the retina. There were two causes for this change. (*a*) The intensity of the light had to be increased quite a great deal from center to periphery to give the chromatic threshold from point to point; and (*b*) the achromatic value of the colors does not remain the same from the center to the periphery of the retina. The gray that matched the stimulus in achromatic value at each point was determined by the equality of brightness method.[1] With reference to these determinations, it may be said that with the stimulus reduced to the chromatic threshold the color difference between the stimulus and the gray was so small that the equality of brightness judgment was not difficult to make. The match was made in every case for the part of the retina under investigation. It had to be attained by a series of approximations. That is, the threshold was first obtained at the given point with no especial control of brightness of preëxposure and surrounding

[1] The Hering papers did not present a sufficiently wide range of reflection coefficients to match the brightness range of the threshold value of the stimulus light from the center to the periphery of the retina. For example, at the threshold of sensation at the center of the retina, the darkest of the Hering papers illuminated by the rather strong light of the room was brighter than the stimulus light; and in the far periphery of the retina through a zone varying in breadth from 2 to 13 degrees for the different colors, the lightest of this series of papers was darker than the stimulus color.

field. The brightness of preëxposure and surrounding field was then made to match this value of the stimulus and the threshold was redetermined. This procedure was repeated until a threshold was obtained that required no further change in these surfaces to match it in brightness. In order to make the specification of the brightness of the preëxposure and the surrounding field independent of the illumination of the room and of the variability of the reflection coefficients of different issues of the Hering papers, the brightness was in each case determined in candlepower per sq. in. This determination was made by means of a Sharp-Millar portable photometer with the test plate removed. The instrument was calibrated against a magnesium oxide surface obtained by depositing the oxide from the burning metal. By this method the reflecting surfaces were used as detached test plates. The readings were converted into candlepower per sq. in. by the following formula: Brightness $= \frac{\text{foot candles}}{\pi \times 144}$.[1] For the sake of reproducibility of conditions from time to time in a given laboratory or in different laboratories, it is obvious that a photometric specification should be given in all cases not only of the general illumination of the room but of the brightness of all surfaces for which precision of control is of importance to the results of the work.

(4) The illumination of the room was kept at a constant value. Two features are necessary for this control. (*a*) A means must be had of detecting small changes of illumination. This may be accomplished by a portable photometer of the Sharp-Millar or Macbeth type, for example, furnished with a daylight screen, or of the simpler type described by the writers in a previous article (5). And (*b*) a means must be had also of producing small variations in the illumination of the room, else the changes due to fluctuations in the external light can not be compensated for with the precision and minuteness of control that is needed. This is accomplished in our optics room by two systems of thin white curtains running

[1] By multiplying these values in turn by 486.8 they may be converted into millilamberts, a term frequently used by engineers to specify small brightness quantities.

on spring rollers beneath the skylight. One of the systems of white curtains and the light-proof curtain run lengthwise of the room; the other system of white curtains runs across the room. By means of the white curtains either small local or small general changes can be produced in the illumination of the room; and by means of the light-proof curtain larger changes may be produced ranging from full illumination to the darkness of a moderately good dark room. The light-proof curtain is of a breadth equal to that of the room and runs in a deep light-tight boxing. The white curtains are narrower and are made to overlap at the edges. These curtains run on wire guides so distributed as to prevent any sagging or wrinkling. Above these curtains are pivoted two large diffusion sashes of glass ground on one side completely filling the skylight opening. These sashes diffuse the light in the room giving an even distribution of illumination and rendering, because of that fact, an even and precise control easier to accomplish. In a careful specification of the conditions under which the work is done a very important item is to give a photometric specification of the illumination of the room. This may be done in foot or meter-candles as desired. If the illumination is uneven it should be done systematically throughout the room. If, on the other hand, it is pretty uniform, it is usually sufficient to give its value in three or more directions at the point of work. In case of the present work, for example, the value of the horizontal component was 30.49 foot candles; the vertical component, 121.95 foot candles; and the 45 degree component, 82.97 foot candles.

(5) The amount of light entering the eye was made independent of variations in the size of the pupil. Independence of change in size of pupil was especially needed in this work because of the large variations in the intensity of light used. Such control is very easy to accomplish with the means of presenting the light to the eye that is used in our apparatus. All that is needed is to keep the image that falls on the pupil of a constant size and smaller than the pupil throughout its entire range of variations in the given series of experiments. Not only can this variation be determined in preliminary

experiments as a guide to the size of the image that is needed, but the image itself can be compared with the pupil at each observation. For details of the method of exercising this control see 'A Substitute for an Artificial Pupil,' Psychol. Rev., 1916, **23**, 380–383.[1]

Results

A statement of the results of the investigation is given in Tables I.–VIII. The nearness of the points investigated to each other was determined by the rapidity with which the sensitivity decreased in the meridian in question. In those regions in which the decrease was gradual the determinations were made at points separated by as much as 5 degrees. In regions, however, where the rate of decrease was rapid or unusual features were present, the determinations were made at points separated only by 1 degree. A graphic representation of the results of these tables is given in Charts I.–IV. In these charts degree of eccentricity is plotted along the abscissa and the value of the threshold in watts (10^7 ergs per sec.) is plotted along the ordinate. In Charts I. and II. the values of the threshold from the center of the retina to the limits of sensitivity are plotted. In case of the red, yellow and blue, it will be remembered from statements made in former papers that the limits of sensitivity for lights of high intensity coincide with the limits of the field of white light vision. This, however, was not the case for the green stimulus. By no increase of intensity were we able to make the limits of green sensitivity coincide with the limits of white light vision. In Charts III. and IV. the above values from the center of the retina through the region of gradual decrease of sensitivity are plotted on a larger scale. This is done because when plotted on the scale used in Charts I. and

[1] Since the article referred to above was published we have devised and constructed a very convenient attachment for our analyzing slit by means of which the length of aperture of the slit may be varied by half millimeter steps. Space will not be taken here for a detailed description of this device. In brief, it consists of two knife edged jaws moving in the vertical, operated by means of a ratchet and spring. Still finer control could be secured, of course, by means of a micrometer screw. Constructed in this latter form the device would be very serviceable as a means of producing finely graded changes of intensity.

II. the curves fall so closely together that the relative sensitivities to the four colors are not clearly represented. That is, the range of the values for the threshold from the center to the extreme periphery of the retina is so great that in Charts I. and II., in which the entire range is represented, a scale value had to be chosen which is so large as almost to obscure the smaller differences in relative sensitivity to the different colors in the region of gradual decrease in sensitivity.

Table I

Chromatic Thresholds for Red, Nasal Meridian

In this table are given the values of the threshold for red (670 $\mu\mu$) at 22 points in the nasal meridian. The intensity of light at the analyzing slit was 94.27×10^{-8} watt.

Degree of Excentricity	Surrounding Field and Pre-exposure. (Candle-power per Sq. In.)	Value of Threshold			
		Degrees Open Sector	Total Amount of Light at Campimeter Opening and at Eye (Watt $\times 10^{-12}$)	Density of Light at Campimeter Opening (Watt $\times 10^{-12}$ per Sq. Mm.)	Density of Light at Eye (Watt $\times 10^{-12}$ per Sq. Mm.)
0	0.000764	0.375	30.80	0.174	9.34
5	0.000764	0.375	30.80	0.174	9.34
10	0.000764	0.438	36.00	0.203	10.90
14–17		Blind Spot			
20	0.000764	0.75	61.70	0.349	18.68
25	0.002125	1.00	82.20	0.465	24.90
30	0.003744	2.50	205.50	1.163	62.25
35	0.005088	3.75	308.30	1.744	93.38
40	0.005088	4.00	328.80	1.860	99.60
45	0.005210	4.50	369.90	2.093	112.05
50	0.005210	5.00	411.00	2.325	124.50
55	0.005902	6.00	493.20	2.790	149.40
60	0.006268	8.00	657.60	3.720	199.20
65	0.006838	12.25	1007.00	5.696	305.00
70	0.007408	20.00	1644.00	9.300	498.00
75	0.01140	23.00	1890.60	10.695	572.70
80	0.01262	26.00	2137.20	12.090	647.40
82	0.01587	34.00	2794.80	15.810	846.60
85	0.02116	50.00	4110.00	23.250	1245.00
87	0.02686	114.00	9370.80	53.010	2838.60
88	0.03093	180.00	14796.00	83.700	4482.00
90	0.05088	270.00	22194.00	125.550	6723.00
92	0.05088	338.00	27783.60	157.170	8416.20

In this and the following tables the light was taken from the spectrum of a Nernst filament operated by 0.6 ampere of current. In all cases the preëxposure and surrounding field were made as nearly as possible the same brightness as the stimulus.

With reference to the results given in Tables I.–VIII., the following points may be noted. (1) The characteristics of response of the eyes for which results are given have been

very widely investigated for both central and peripheral vision. They have been chosen for this and other work especially because of their normality and practised precision of behavior. Their spectrum luminosity curve, for example, agrees (6) very closely with the average curve obtained by

Table II

Chromatic Thresholds for Red, Temporal Meridian

In this table are given the values of the threshold for red (670 $\mu\mu$) at 25 points in the temporal meridian. The intensity of light at the analyzing slit was 94.27×10^{-8} watt.

Degree of Excentricity	Surrounding Field and Pre-exposure. (Candle-power per Sq. In.)	Value of Threshold			
		Degrees Open Sector	Total Amount of Light at Campimeter Opening and at Eye (Watt $\times 10^{-12}$)	Density of Light at Campimeter Opening (Watt $\times 10^{-12}$ per Sq. Mm.)	Density of Light at Eye (Watt $\times 10^{-12}$ per Sq. Mm.)
0	0.000764	0.375	30.80	0.174	9.34
5	0.000764	0.375	30.80	0.174	9.34
10	0.000764	0.438	36.00	0.203	10.90
15	0.000764	0.75	61.70	0.349	18.68
20	0.002125	1.00	82.20	0.465	24.90
25	0.003867	2.75	226.10	1.279	68.48
30	0.005902	8.00	657.60	3.720	199.20
33	0.006431	14.00	1150.80	6.510	348.60
35	0.007408	17.00	1397.40	7.905	423.30
40	0.01404	29.00	2383.80	13.485	722.10
44	0.01791	38.00	3123.60	17.670	946.20
45	0.02686	104.00	8548.80	48.360	2589.60
46	0.03093	160.00	13152.00	74.400	3984.00
47	0.03663	216.00	17755.20	100.440	5378.40
48	0.03663	216.00	17755.20	100.440	5378.40
49	0.03663	216.00	17755.20	100.440	5378.40
50	0.03663	216.00	17755.20	100.440	5378.40
51	0.03663	216.00	17755.20	100.440	5378.40
52	0.03663	216.00	17755.20	100.440	5378.40
53	0.03663	216.00	17755.20	100.440	5378.40
54	0.03663	216.00	17755.20	100.440	5378.40
55	0.03663	245.00	20139.00	113.925	6100.50
58	0.05088	270.00	22194.00	125.550	6723.00
60	0.05088	300.00	24660.00	139.500	7470.00
61	0.05088	315.00	25893.00	146.475	7843.50

Nutting (7) for 18 observers. Also their normality of chromatic response has, at various times, been checked up by a number of observers. Data on this point may be found in nearly all of the work that has been published from this laboratory. In case of the present work the systematic point by point determination has been made only upon the one

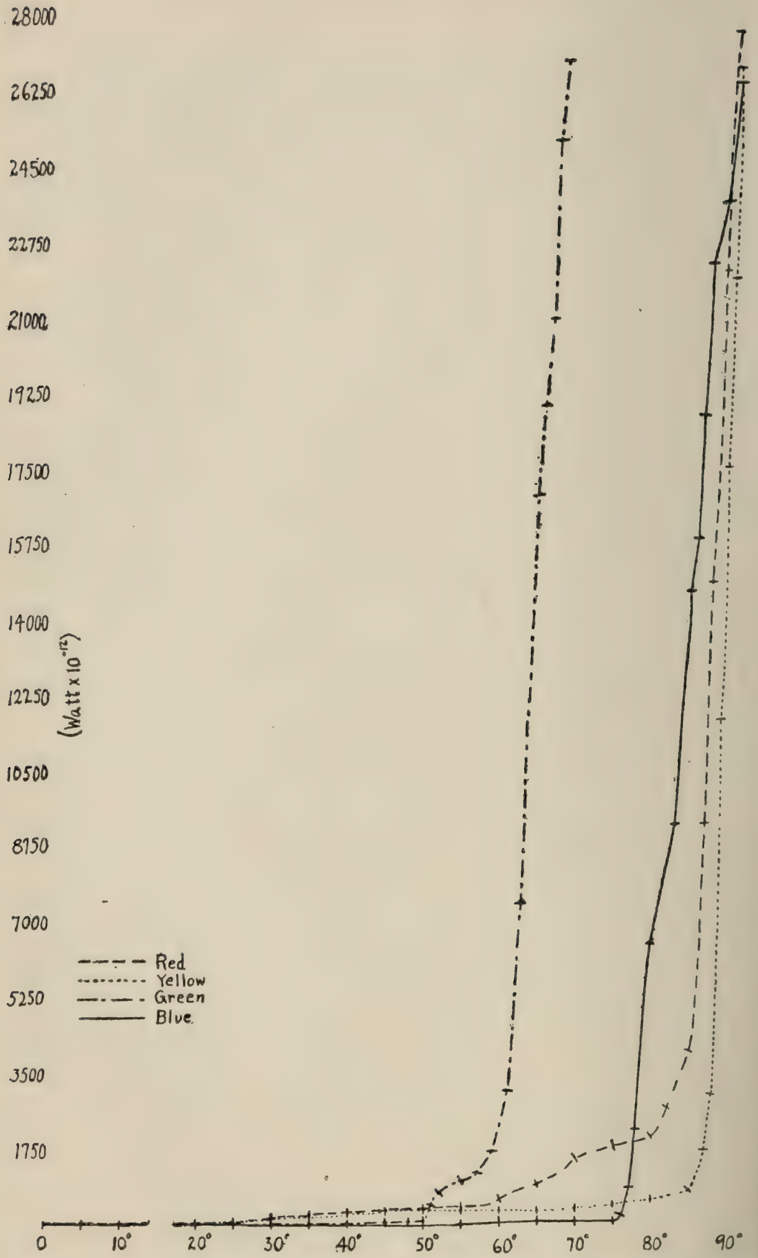

CHART I. Chromatic Thresholds for the Four Colors, Nasal Meridian. In this chart and Chart II., degree of excentricity in the field of vision is plotted along the abscissa and the value of the threshold along the ordinate. Of the three values of the threshold given in the tables, the total amount of light at the campimeter opening and at the eye is represented.

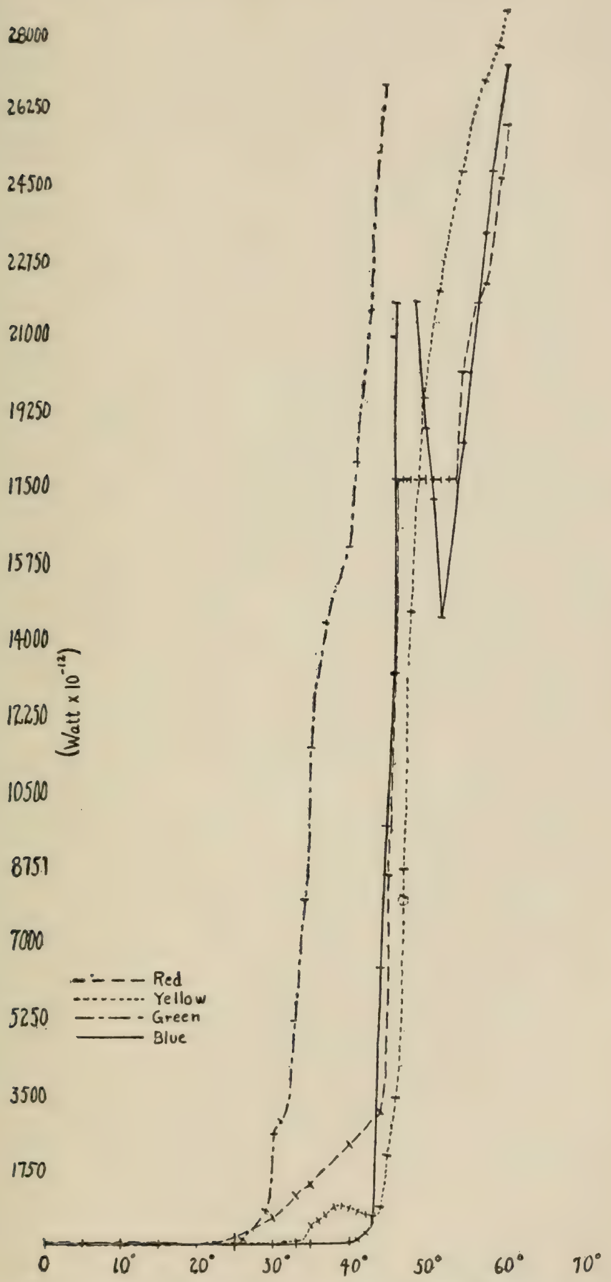

CHART II. Chromatic Thresholds for the Four Colors, Temporal Meridian.

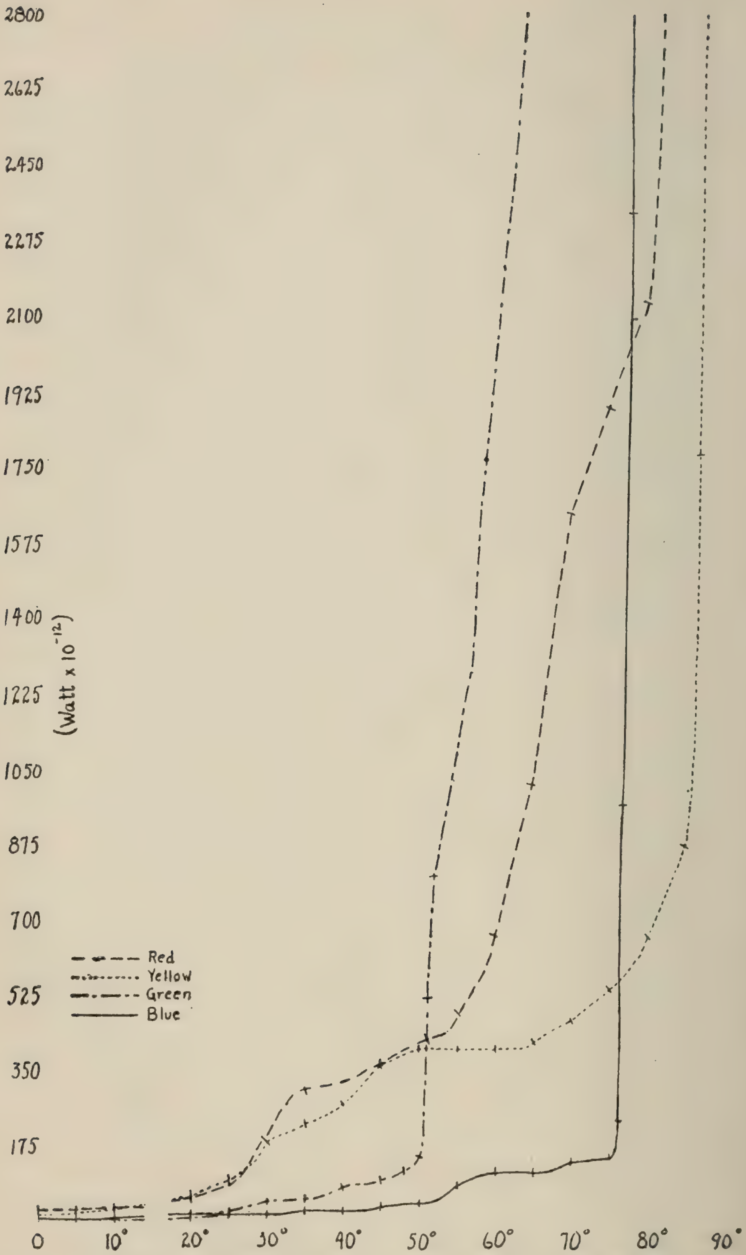

CHART III. Chromatic Thresholds for the Four Colors, Nasal Meridian. In this chart and Chart IV., the values represented in Charts I. and II. respectively, from the center of the retina through the region of gradual decrease of sensitivity are plotted on a larger scale. This is done because when plotted on the scale used in Charts I. and II., the curves fall so closely together that the relative sensitivities are not clearly represented.

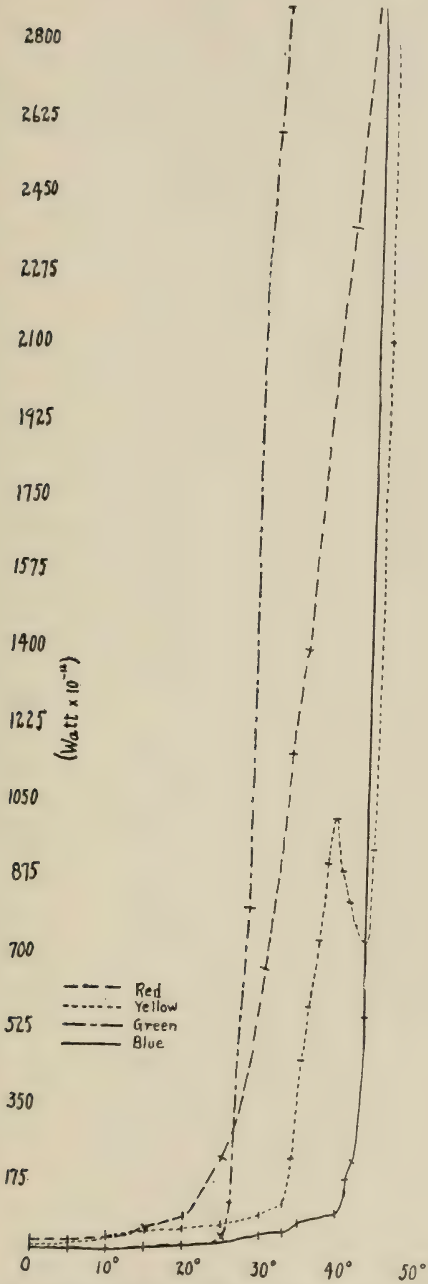

CHART IV. Chromatic Thresholds (enlarged scale) for the Four Colors, Temporal Meridian.

observer. However, one or more check observers have been used on points of the work of especial importance to theory, such as the irregular distribution of sensitivity to the pairs of colors, the criss-crossing or interlacing of limits, the areas analogous in type to the Schumann case of color-blindness, the deficiency of sensitivity of the far periphery of the retina to green, and the inability to get a red or green that is stable in color tone for all parts of the retina.

Table III

Chromatic Threshold for Yellow, Nasal Meridian

In this table are given the values of the threshold for yellow (581 $\mu\mu$) at 23 points in the nasal meridian. The intensity of light at the analyzing slit was 93.10×10^{-8} watt.

Degree of Excentricity	Surrounding Field and Pre-exposure (Candle-power per Sq. In.)	Value of Threshold			
		Degrees Open Sector	Total Amount of Light at Campimeter Opening and at Eye (Watt $\times 10^{-12}$)	Density of Light at Campimeter Opening (Watts $\times 10^{-12}$ per Sq. Mm.)	Density of Light at Eye (Watt $\times 10^{-12}$ per Sq. Mm.)
0	0.002125	0.20	16.30	0.092	4.94
5	0.002125	0.25	20.40	0.115	6.175
10	0.002125	0.375	30.56	0.172	9.263
14–17		Blind Spot			
20	0.003378	0.75	61.13	0.346	18.525
25	0.003867	1.25	101.88	0.576	30.875
30	0.006431	2.375	193.56	1.094	58.663
35	0.006919	2.875	234.31	1.325	71.013
40	0.006956	3.50	285.25	1.614	86.450
45	0.007326	4.50	366.75	2.074	111.150
50	0.007408	4.875	397.31	2.247	120.413
55	0.007408	4.875	397.31	2.247	120.413
60	0.007977	5.00	407.50	2.305	123.500
65	0.008547	5.125	417.69	2.363	126.588
70	0.009768	5.75	468.63	2.651	142.025
75	0.01140	6.75	550.13	3.112	166.725
80	0.01384	8.00	652.00	3.688	197.600
85	0.01404	10.75	876.13	4.956	265.525
87	0.01587	22.00	1793.00	10.142	543.400
88	0.02523	38.00	3097.00	17.518	938.600
89	0.03093	144.00	11736.00	66.384	3556.800
90	0.05088	216.00	17604.00	99.576	5335.200
91	0.05088	270.00	22005.00	124.47	6669.000
92	0.05088	330.00	26895.00	152.130	8151.000

(2) Up to 15–20 degrees the accuracy of the threshold values is doubtless lessened by the difficulty of making and reading the adjustments for such small open sectors, even with our micrometer device for making the adjustment and the

Vernier scale for reading it. On this account it may well be that the threshold at the center is somewhat high for all of the colors, inasmuch as open sectors of less than one-tenth of a degree are rather infeasible to use. For the exact deter-

TABLE IV

CHROMATIC THRESHOLDS FOR YELLOW, TEMPORAL MERIDIAN

In this table are given the values of the threshold for yellow (581 $\mu\mu$) at 29 points in the temporal meridian. The intensity of light at the analyzing slit was 93.10 $\times$ 10^{-8} watt.

Degree of Excentricity	Surrounding Field and Pre-exposure. (Candle-power per Sq. In.)	Value of Threshold			
		Degrees Open Sector	Total Amount of Light at Campimeter Opening and at Eye (Watt $\times$ 10^{-12})	Density of Light at Campimeter Opening (Watt $\times$ 10^{-12} per Sq. Mm.)	Density of Light at Eye (Watt $\times$ 10^{-13} per Sq. Mm.)
0	0.002125	0.20	16.30	0.092	4.94
5	0.002125	0.25	20.38	0.115	6.175
10	0.003175	0.50	40.75	0.231	12.350
15	0.003378	0.625	50.94	0.288	15.438
20	0.003456	0.75	61.13	0.346	18.525
25	0.003867	0.875	71.31	0.403	21.613
30	0.005210	1.125	91.69	0.519	27.788
33	0.005779	1.50	122.25	0.692	37.050
34	0.007326	2.75	224.13	1.268	67.925
35	0.009768	4.50	366.75	2.075	111.150
36	0.01140	7.00	570.50	3.227	172.900
37	0.01262	9.00	733.50	4.149	222.300
38	0.01262	11.25	916.88	5.186	277.875
39	0.01262	12.50	1018.75	5.763	308.750
40	0.01262	11.00	896.50	5.071	271.700
41	0.01262	10.00	815.00	4.610	247.000
42	0.01262	9.50	774.25	4.380	234.650
43	0.01262	9.00	733.50	4.149	222.300
44	0.01262	11.50	937.25	5.302	284.050
45	0.01404	26.00	2119.00	11.986	642.200
46	0.01791	42.00	3423.00	19.362	1037.400
47	0.02686	106.00	8639.00	48.866	2618.200
48	0.05088	180.00	14670.00	82.980	4446.000
50	0.05088	240.00	19560.00	110.640	5928.000
52	0.05088	270.00	22005.00	124.470	6669.000
55	0.05088	304.00	24776.00	140.144	7508.800
58	0.05088	330.00	26895.00	152.130	8151.000
60	0.05088	340.00	27710.00	156.740	8398.000
61	0.05088	350.00	28525.00	161.350	8645.000

mination of the absolute values of the threshold in this part of the retina, the discs can be used with more accuracy when a substantial reduction is first made by means of some other device. In considering the absolute values given above, the state of general adaptation of the eye must also be kept in

mind. The horizontal component of illumination at the point of work was, it will be remembered, 30.49 foot-candles; the vertical component, 121.95 foot-candles; and the 45 degree component, 82.97 foot-candles.

Table V

Chromatic Thresholds for Green, Nasal Meridian

In this table are given the values of the threshold for green (522 $\mu\mu$) at 23 points in the nasal meridian. The intensity of light at the analyzing slit was 91.50×10^{-8} watt.

Degree of Excentricity.	Surrounding Field and Pre-exposure (Candle-power per Sq. In.)	Valne of Threshold			
		Degrees Open Sector	Total Amount of Light at Campimeter Opening and at Eye (Watt $\times 10^{-12}$)	Density of Light at Campimeter Opening (Watt $\times 10^{-12}$ per Sq. Mm.)	Density of Light at Eye (Watt $\times 10^{-12}$ per Sq. Mm.)
0	0.002125	0.10	8.00	0.045	2.425
5	0.002125	0.10	8.00	0.045	2.425
10	0.002125	0.125	10.00	0.057	3.031
14–17		Blind Spot			
20	0.003175	0.167	13.33	0.076	4.042
25	0.003378	0.375	30.00	0.170	9.094
30	0.003744	0.625	50.00	0.283	15.156
35	0.003867	0.75	60.00	0.340	18.188
40	0.005210	1.00	80.00	0.453	24.250
45	0.005779	1.25	100.00	0.566	30.313
48	0.005983	1.50	120.00	0.680	36.375
50	0.006268	1.875	150.00	0.849	45.468
51	0.006919	6.50	520.00	2.945	157.625
52	0.007408	10.00	800.00	4.530	242.500
55	0.007977	13.50	1080.00	6.116	327.375
57	0.008954	16.00	1280.00	7.248	388.000
59	0.01018	22.50	1770.00	10.193	545 625
61	0.01425	40.00	3200.00	18.120	970.000
63	0.02116	94.00	7520.00	42.582	2279.500
65	0.02686	212.00	16960.00	96.036	5141.000
66	0.03093	238.00	19040.00	107.814	5771.500
67	0.03663	263.00	21040.00	119.139	6377.750
68	0.05088	315.00	25200.00	142.695	7638.750
69	0.05088	338.00	27040.00	153.114	8196.500

(3) The numerical values in Column 1 of these tables represent, of course, points in the field of vision. What the corresponding points on the retina are, could not be determined without knowing the net displacement, if there be such displacement, of the image towards the principal axis of the refracting system as the beam of light enters the eye more and more obliquely. Just what the factors are that might contribute to this displacement in a refracting system so

complex as that of the eye, is somewhat difficult to determine. The following are perhaps worthy of consideration: the difference in the optical density of the media traversed by the incident and the emergent rays, and the greater combined refracting power of the cornea and the anterior surface of the lens than of the posterior surface of the lens. Another

TABLE VI

CHROMATIC THRESHOLDS FOR GREEN, TEMPORAL MERIDIAN

In this table are given the values of the threshold for green (522 $\mu\mu$) at 19 points in the temporal meridian. The intensity of light at the analyzing slit was 91.50 $\times$ 10^{-8} watt.

Degree of Excentricity	Surrounding Field and Pre-exposure. (Candle Power per Sq. In.)	Value of Threshold			
		Degrees Open Sector	Total Amount of Light at Campimeter Opening and at Eye (Watt $\times$ 10^{-12})	Density of Light at Campimeter Opening (Watt $\times$ 10^{-12} per Sq. Mm.)	Density of Light at Eye (Watt $\times$ 10^{-12} per Sq. Mm.)
0	0.002125	0.10	8.00	0.045	2.425
5	0.002125	0.125	10.00	0.057	3.031
10	0.002125	0.125	10.00	0.057	3.031
15	0.003175	0.167	13.33	0.076	4.042
20	0.003378	0.25	20.00	0.113	6.063
25	0.003456	0.375	30.00	0.170	9.094
26	0.005779	1.50	120.00	0.680	36.375
28	0.007408	10.00	800.00	4.530	242.500
30	0.01018	32.00	2560.00	14.496	776.000
31	0.01140	36.00	2880.00	16.308	873.000
33	0.01384	65.00	5200.00	29.445	1576.250
34	0.02116	100.00	8000.00	45.300	2425.000
35	0.02523	144.00	11520.00	65.232	3497.000
37	0.02686	180.00	14400.00	81.540	4365.000
40	0.02686	201.50	16120.00	91.280	4886.375
41	0.03093	226.00	18080.00	102.378	5480.500
43	0.03663	270.00	21600.00	122.310	6547.500
44	0.05088	305.00	24400.00	138.165	7396.250
45	0.05088	335.00	26800.00	151.755	8123.750

thing which should be taken into consideration in the use of the campimeter, is the fact that the front of the cornea, and not the optic center of the refracting system of the eye (roughly speaking), is the point from which the graduations on the instrument are laid out. From considerations such as these, it can be understood, perhaps, why an object of an excentricity of 92° as read on the campimeter scale, or approximately 2° back of the plane tangent to the anterior surface of the cornea at or near the point of entrance of the line of

regard, is still visible. In this connection the difference in the curvature of the cornea of different eyes should also be taken into account.

Table VII

Chromatic Thresholds for Blue, Nasal Meridian

In this table are given the values of the threshold for blue (468 $\mu\mu$) at 26 points in the nasal meridian. The intensity of light at the analyzing slit was 91.97×10^{-8} watt.

Degree of Excentricity	Surrounding Field and Pre-exposure. (Candle-power per Sq. In.)	Value of Threshold			
		Degrees Open Sector	Total Amount of Light at Campimeter Opening and at Eye (Watt $\times 10^{-12}$ per Sq. Mm.)	Density of Light at Campimeter Opening (Watt $\times 10^{-12}$ per Sq. Mm.)	Density of Light at Eye (Watt $\times 10^{-12}$ per Sq. Mm.)
0	0.000764	0.10	8.06	0.046	2.440
5	0.000764	0.10	8.06	0.046	2.440
10	0.002125	0.167	13.40	.076	4.067
14–17		Blind Spot			
20	0.002125	0.25	20.15	0.114	6.100
25	0.002125	0.25	20.15	0.114	6.100
30	0.003175	0.25	20.15	0.114	6.100
35	0.003378	0.375	30.23	0.171	9.150
40	0.003456	0.375	30.23	0.171	9.150
45	0.003744	0.50	40.30	0.228	12.200
50	0.003744	0.625	50.38	0.285	15.250
55	0.003867	1.125	90.68	0.513	27.450
60	0.003867	1.50	120.90	0.684	36.600
65	0.003867	1.50	120.90	0.684	36.600
70	0.003867	1.75	141.05	0.798	42.700
75	0.003867	1.875	151.10	0.855	45.750
76	0.003989	3.00	241.80	1.368	73.200
77	0.005210	12.00	967.20	5.472	292.800
78	0.005779	29.00	2337.40	13.224	707.600
80	0.006956	82.00	6609.20	37.392	2000.800
83	0.01262	116.00	9349.60	52.896	2830.300
85	0.03093	183.00	14749.80	83.448	4465.200
86	0.03093	198.00	15958.80	90.288	4831.200
87	0.03663	234.00	18860.40	106.704	5709.600
88	0.03663	277.00	22326.20	126.312	6758.800
90	0.05088	295.00	23777.00	134.520	7198.000
92	0.05088	328.00	26436.80	149.568	8003.200

That there is this wide extension of the field of vision in the temporal meridian seems to be well established by other investigators. Baas, for example, quoted by de Schweinitz (8), finds the average limit for ten observers to be 99°. Traquair (9) and others also find the limits to extend beyond 90°. In our own work we have found it to be carried out as far as 92° in a number of cases. For the explanation of this

Table VIII

Chromatic Thresholds for Blue, Temporal Meridian

In this table are given the values of the threshold for blue (468 $\mu\mu$) at 26 points in the temporal meridian. The intensity of light at the analyzing slit was 91.97×10^{-8} watt.

Degree of Excentricity	Surrounding Field and Pre-exposure. (Candle-power per Sq. In.)	Value of Threshold			
		Degrees Open Sector	Total Amount of Light at Campimeter Opening and at Eye (Watt $\times 10^{-12}$)	Density of Light at Campimeter Opening (Watt $\times 10^{-12}$ per Sq. Mm.)	Density of Light at Eye (Watt $\times 10^{-12}$ per Sq. Mm.)
0	0.000764	0.10	8.06	0.046	2.440
5	0.000764	0.10	8.06	0.046	2.440
10	0.000764	0.10	8.06	0.046	2.440
15	0.002125	0.167	13.40	0.076	4.067
20	0.002125	0.25	20.15	0.114	6.100
25	0.003175	0.375	30.23	0.171	9.150
30	0.003378	0.625	50.38	0.285	15.250
33	0.003456	0.75	60.45	0.342	18.300
35	0.003456	1.00	80.60	0.456	24.400
40	0.003744	1.25	107.50	0.570	30.500
41	0.003867	2.25	181.35	1.026	54.900
42	0.005088	4.00	322.40	1.824	97.600
43	0.005779	7.00	564.20	3.192	170.800
44	0.01262	80.00	6448.00	36.480	1952.000
45	0.03093	120.00	9672.00	54.720	2928.000
46	0.03093	164.00	13218.40	74.784	4001.600
46.5	0.03663	270.00	21762.00	123.120	6588.000
47–48			Blind to Blue		
49	0.03663	270.00	21762.00	123.120	6588.000
50	0.03663	234.00	18860.40	106.704	5709.600
52	0.03663	180.00	14508.00	82.080	4392.000
55	0.03663	230.00	18538.00	104.880	5612.000
56	0.03663	250.00	20150.00	114.000	6100.000
57	0.05088	270.00	21762.00	123.120	6588.000
58	0.05088	290.00	23374.00	132.240	7076.000
59	0.05088	306.00	24663.60	139.536	7466.400
61	0.05088	338.00	27242.80	154.128	8247.200

fact there is of course the alternative possibility of a loss of exact fixation, which possibility we have not ignored in our own thinking. However, if there is a loss of fixation, we have not been able to detect it by any means we have as yet been able to devise.

Discussion of Results

From data such as are presented in these tables and charts the following comparisons may be made in so far as the threshold may be regarded as a measure of sensitivity: (*a*) the sensitivity to a given range of wave-lengths from point to point

in the same meridian; (*b*) the sensitivity at corresponding points in different meridians; and (*c*) the sensitivity to the different wave-lengths in any given meridian. From the latter comparison, if properly made, an estimate of the selectiveness of the chromatic response at the threshold of sensation may be had. In making these comparisons several points of interest may be noted.

(1) *The Irregularities in the Curve of Sensitivity for the Different Colors in a Given Meridian.*—The rate of decrease in sensitivity after a certain degree of excentricity has been reached shows a great irregularity for the individual colors. This irregularity is greater in the temporal than in the nasal meridian. The following are some of the more notable examples. (*a*) The plateau in the curve for red in the temporal meridian. That is, the curve representing the amounts of energy required to arouse the just noticeable red sensation in this meridian rises almost imperceptibly from the center of the retina to about 20 degrees. From there it rises sharply to about 44 degrees. From 44 to 47 degrees the curve is almost vertical. Between these two points the energy required to arouse just noticeable sensation changes from 31.236×10^{-10}–177.552×10^{-10} watt. From 47 to 54 degrees occurs the plateau referred to. Between these two points there is practically no change in sensitivity. (*b*) The hump in the curve for yellow in the temporal meridian occurring between 33 and 43 degrees. From 36 to 39 degrees there is a sharp drop in sensitivity and from there to 43 degrees almost as sharp a rise. Between 36 and 39 degrees the energy required to arouse just noticeable sensation changed from 5.705×10^{-10} to 10.188×10^{-10} watt. This is an area of deficiency or partial blindness to yellow. There is in this area no corresponding loss in sensitivity to the blue stimulus nor to the other colors. Moreover, there is no detectable change in the cancelling or after-image reactions to yellow. That is, this area shows the characteristics of the Schumann case of color blindness. (*c*) The quick rise in the curve for all of the colors near the limits of sensitivity. This feature is very marked both in the nasal and temporal meridians, but more marked in the nasal than

in the temporal meridian. In the temporal meridian the rise begins around 45 degrees for red, yellow and blue and at 26 degrees for green. In the nasal meridian it begins around 75 to 85 degrees for red, yellow and blue; and at 51 degrees for green. In this region were found the limits of sensitivity in our previous work with the Hering pigment papers with the degree of illumination, etc., employed. And (*d*) the area of total blindness to blue from 47 to 49 degrees in the temporal meridian. On all sides of this area is a border of lowered sensitivity, the sensitivity falling off quite sharply as the area is approached. This area also shows the characteristics of the Schumann case of color blindness. That is, there is no corresponding decrease in sensitivity to yellow, red or green and no corresponding change in the cancelling or after-image reactions.

(2) *The Great Difference in Sensitivity at Corresponding Points in the Temporal and Nasal Meridians, more Especially in the more Remote Portions of the Retina.*—This difference is already so well known in a general way as to need no especial discussion here. Our data, however, may be considered as contributive in two regards: (*a*) the large number of points investigated and (*b*) the rating of the stimuli in units that can be compared numerically. In comparing the distribution of sensitivity at corresponding points in the two meridians it may be of interest among other things to note the difference in the order in which the sensitivity to the different colors falls off in case of red, yellow and blue as the limits of sensitivity are approached. So far as the relative sensitivity to red and green is concerned, this point bears upon the changes in the color tone of red in the two meridians in passing from the center to the periphery of the retina. As will be noted later in a more detailed statement of color tone changes, the red stimulus employed in the investigation was sensed as red in the nasal meridian from the center to 60 degrees, from 60 to 86 degrees as yellowish red or orange, and 86 to 92 degrees as red. In the temporal meridian it was sensed as red from the center to 30 degrees, from 30 to 47 degrees as yellowish red or orange and from 47 to 61 degrees as red. That

is, the zone in the far periphery of the retina in which the weakly aroused yellow component of the excitation is below the threshold in red, is relatively broader in the temporal than in the nasal meridian, as the relation of the curves of sensitivity to red and yellow would indicate should be the case.

(3) *The Striking Absence of Uniformity of Ratio of Sensitivity to the Pairs of Colors, Red and Green, and Blue and Yellow, from Center to Periphery of the Retina.*—From the center to about 27 degrees in the temporal meridian and about 51 degrees in the nasal meridian, the sensitivity to green is greater than to red. At these points a radical reversal of sensitivity takes place and the sensitivity to red is much greater than to green. A reversal of sensitivity occurs also for blue and yellow; but at a point farther removed from the center of the retina, namely, at about 44 degrees in the temporal meridian and at about 77 degrees in the nasal meridian. Even up to the points of reversal with their radical deviations in relative sensitivity, an inspection of the charts, especially III. and IV., will show how very little ground there is for any claim that constancy of ratio exists between the colors red and green, and blue and yellow from center to periphery of the retina. (A further discussion of this point will be given in the second part of this paper: 'Bearing of Results on Color Theory.')

And (4) *the Correspondence of the Distribution of Sensitivity to Red, Green and Yellow with what might be expected from the Changes in the Color Tone of Red and Green in Passing from the center to the periphery of the retina.*—For example, in passing from the center to the periphery of the retina the red stimulus used in making the threshold determinations given in the foregoing curves was sensed as red from the center to about 60 degrees; from 60 degrees to about 86 degrees it was sensed as a yellowish red or orange; and from 86 degrees to the limits of sensitivity it was sensed again as red. Corresponding to this, it will be noted that there is in this meridian a fairly close agreement in sensitivity to red and yellow from the center to about 60 degrees, at which point there is a rela-

tively sharp decrease in sensitivity to red. That is, from about 60 to 86 degrees there is much less sensitivity to red than to yellow. At about 86 degrees there is a sharp decrease in sensitivity to yellow, and from this point on to the limits of sensitivity a fairly close agreement again in sensitivity to the two colors. In the temporal meridian the red stimulus was sensed as red from the center of the retina to about 30 degrees; from there to about 47 degrees as yellowish red or orange; and from 47 degrees to the limits of sensitivity as red. Similarly in this meridian there is a fairly close agreement in sensitivity to red and yellow from the center to about 30 degrees; from 30 degrees to about 47 degrees there is considerably greater sensitivity to yellow than to red; and from this point on to the limits greater sensitivity to red than to yellow. In case of green, in the nasal meridian the greater loss in sensitivity to green as compared with yellow begins at about 51 degrees; and in the temporal meridian at about 26 degrees. Correspondingly at these points the green stimulus began to be sensed as yellowish green and continued to be sensed in this tone until the limits of sensitivity to green were reached, from which point on for a short distance it was sensed as yellow.

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CHROMATIC THRESHOLDS OF SENSATION FROM CENTER TO PERIPHERY OF THE RETINA AND THEIR BEARING ON COLOR THEORY—PART II

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As was stated in Part I., one of the incentives to this investigation was to clear up two points in relation to color theory. These points are as follows:

1. The claim has been made by followers of the Hering theory that the sensitivity of the retina to the pairs of colors: red and green, and blue and yellow, falls off in a constant ratio from the center to the periphery of the retina. This claim, it will be remembered, was made first by Hess (1) on the grounds of an investigation of the relative limits of sensitivity with colors equalized both in cancelling power and brightness; and was given a great deal of importance by Hering (2) in a companion article in refutation of a revision of the Young-Helmholtz theory made independently by Fick (3) and Leber (4) to explain the color blindness of the peripheral retina. Fick, for example, assumed that from the middle towards the periphery of the retina the relative excitability of the three nerve fibers to lights of the various wave-lengths constantly alters in such a way that at a certain distance from the fovea, namely, in the zone called by Helmholtz red-blind, the red sensing fibers possess the same excitability as the green sensing fibers towards lights of all wave-lengths; and that further towards the extreme periphery all differences between the relative excitability of the three fibers diminish and finally disappear. In the red-blind zone, then, the intensity curves for the red and green sensing fibers coincide, and in the totally color-blind zone, the curves for all three coincide. Curves drawn in accord with these assumptions will, it is contended by Fick, explain the types

of color-blindness found in the peripheral retina without violating any of the fundamental principles of the Young-Helmholtz theory. Helmholtz accepts the essential points of this modification and incorporates them in his theory in his later edition of the 'Physiologische Optik' (**5**). With stimuli equalized in cancelling power and brightness, however, Hess claimed to find a coincidence of the limits for the pairs of colors used, and contended therefrom that the sensitivity to the pairs of antagonistic colors falls off uniformly from the center to the periphery of the retina or that a constant ratio of sensitivity to these colors obtains throughout the retina. (See also in this connection the papers of Bull (**6**), Hegg (**7**), and Baird (**8**).)

Prior to the presentation of a direct disproof of Hess's conclusion that a constant ratio of sensitivity to the paired colors obtains throughout the retina, in the form of results obtained in a detailed investigation of sensitivity from center to periphery, we had pointed out in a previous paper (**9**) that his conclusion was not warranted by the work and results on which it was based. It was based, it will be remembered, on the twofold assumption that if in passing from center to periphery sensitivity ends at the same point of the retina for two stimuli which have equal power to arouse sensation at the center, (*a*) they must still have equal power to arouse sensation at the periphery and (*b*) sensitivity must have fallen off as much for the one as for the other and evenly and uniformly from point to point. This assumption in the first place begins with a fallacy, for the stimuli were not equalized in power to arouse sensation but in cancelling power. Cancelling power and the power to arouse sensation are, as we have already pointed out, not at all equivalent (**10**). In the second place the assumption is itself incorrect; for because of the abrupt decrease in sensitivity with stimuli of medium and high intensities as the limits are approached, the relative sensitivity to the two colors may have changed greatly even assuming an even grading in the loss of sensitivity for each color from the center out, and still the deviations from equal sensitivity not make a difference of as much as 1 de

gree in the limits for the two colors. We have found, for example, that working with pigment colors of good saturation under an illumination of 390 foot-candles, it takes, varying with the color and the meridian investigated, 90 to 120 degrees of color mixed with a gray of the brightness of the color to make a difference of 1 degree in the limits. But an even grading in the loss of sensitivity can not be assumed as the results given in this study show; hence even if it could be demonstrated that the same ratio holds at the limits or at any point well removed from the center, as at the center, the conclusion could not be drawn that constancy of ratio obtains between these points. On this question it is obvious that a conclusion is not warranted unless a point to point investigation is made, and such an investigation shows that striking irregularity and not constancy and uniformity characterizes the changes in sensitivity from the center to the periphery of the retina. And in the third place, when the results of Bull, Hess and Baird who all claimed coextensive limits are examined in detail, it is found that they show the same sort of deviation from coincidence from meridian to meridian as were obtained by Kirschmann and by us, who have made a point of lack of coincidence when stimuli of the same order of intensity are employed. Baird, for example, who determined the limits for red, green, blue, and yellow stimuli in eight meridians in the dark room by means of a perimeter, concludes: "The results show that the zone of stable red is coincident with that of stable green and that the zone of stable yellow is coextensive with that of stable blue" (**11**). An inspection of his results shows, however, that the coincidence is extremely rough. In case of the results for every observer it is found that in some meridians the green field is narrower than the red by 1, 2 or 3 degrees; in other meridians there is coincidence of limits; and in still other meridians the red field is narrower than the green by 1, 2 or 3 degrees. The same is true of blue and yellow, the deviations from coincidence ranging from 1°–5°. Hess and Bull's results show similar variations, in some cases even greater in amount. It seems probable from their conclusions concerning the coincidence of limits, that

they regarded these variations as insignificant. But it should be borne in mind that 2 or 3 degrees of difference in limits is not insignificant when conclusions with regard to the relative sensitivity of the peripheral retina to the complementary colors are to be drawn from the results. Because of the abrupt falling off in sensitivity before the limits are reached with stimuli of medium and high intensities, a difference of 2 or 3 degrees in the limits represents quite a large difference in sensitivity. For example, according to our results with the Hering standard papers under 390 foot-candles of illumination (vertical component), a difference of 2 degrees in the limits represents a difference in sensitivity sufficient to raise the threshold for yellow 120 degrees; for green, 100 degrees; for red, 160 degrees; and for blue 160 degrees. And a difference of 3 degrees represents sufficient difference in sensitivity to raise the threshold for yellow 210 degrees; for green, 215 degrees; for red, 210 degrees; and for blue, 215 degrees. Our results with the more intense spectrum lights show, as might be expected, that a difference of 2 or 3 degrees in the limits represents a still greater difference of sensitivity. This should be quite obvious from the curves we have given in Part I. It is scarcely needful to note in this connection also that the weaker are the stimuli employed, the nearer will the limits be to the center of the retina; and it should be clear from the curves we have given that the nearer the limits are to the center of the retina, the closer will be the approximation to coincidence. Bull, Hegg, Hess and Baird in their attempts to equalize their stimuli both in cancelling power and brightness must have worked with colors of comparatively low saturation, hence with stimuli unduly favorable to coincidence of limits. Their results, therefore, are the product of a special method of working rather than are representative of the relations of sensitivity actually existing in the more remote periphery of the retina even so far as these relations can be judged from a determination of limits alone. Unfortunately no specification of the intensity of their stimuli was given, but the narrowness of the zones of sensitivity obtained indicate that stimuli of low color arousing power were used.

It may be of some interest also to note in this connection that the present writers have never been able to secure red, green, blue and yellow stimuli of spectrum purity, all equal in brightness and at the same time to have the pairs of complementary colors in cancelling proportions. To conceive that the spectrum colors can be equalized at one and the same time with regard to these two independent variables would seem *a priori* to be a logical impossibility; and the task of making this twofold equalization has as yet proved too difficult for us as a practical problem. It might perhaps be done if a variable weighting factor, namely, colorless light, were introduced in the right proportions into the composition of a part or all of the stimuli, but that would scarcely be compatible with the purpose of the investigation. It is, in fact, difficult to understand why such an equation should ever have been attempted in the first place in an investigation of chromatic sensitivities. An equation in the power to arouse the chromatic response is, so far as we can see, the only subjective equation that could be rightfully given a place in the determination of the relative limits of chromatic sensitivity, and this only in a determination of whether or not the same ratio of sensitivity holds for the limits as for the center or other point at which the equation was made. That is, if it does hold, the limits would be coincident, and if it does not hold, they would not be coincident; but no definite knowledge would be gained of the amount of deviation from equality of ratio, nor would any inference be justified with regard to the relative values of the ratio between the point at which the equation was made and the limits. Just what would be accomplished by an equation in cancelling power which neither equalizes the stimuli in intensity nor in power to arouse the chromatic response, is far from clear. Had the object of the investigation been a determination of whether or not constancy in cancelling proportions holds for all parts of the retina, the verdict would be different. For one type of investigation of this sort, then, the equation would be of service, but for an investigation of constancy of ratio of sensitivity, it is obviously irrelevant. There seems also to

be no more experimenal justification and little if any more *a priori* plausibility for the equation in brightness for a determination of the relative limits of chromatic sensitivity; for (*a*) it does not equate the stimuli in power to arouse the chromatic response, (*b*) neither does it equate them in intensity (the equation is merely of the very selective achromatic response to the stimuli), and (*c*) so far as the effect of the achromatic on the chromatic component of the excitation is concerned (the final variable factor that might be considered), it has already been shown by one of us in a previous article (**12**) that there is not enough difference in this effect for the colors used to change the limits of sensitivity by a detectable amount. However, the irrelevancy and the positive disadvantage of such equations, as they appear to us, have been discussed in detail in the previous paper. The question is raised again here only because the results of our point to point investigation throw additional light on the effect that the attempt to treat the stimuli in this way would have on determinations of the type under consideration, namely, compelling the use of stimuli of such low color arousing power as to make the conditions unduly favorable for a coincidence of limits.

But of much greater importance than all of this as a general consideration, is the realization that the determination of the relative or apparent limits for the purpose of ascertaining whether or not a constant ratio of sensitivity to the paired colors obtains throughout the retina, falls far short of its objective. The information sought can be obtained only by a point to point investigation of sensitivity. With the passing then of the belief in any especial significance of the determination of the relative limits, which after all is only a very inadequate way of comparing sensitivities at a limited number of points and which was given undue importance in relation to theory by the failure of Hess and his followers to realize that great irregularity and not uniformity characterizes the decrease of sensitivity from the center to the periphery of the retina, will doubtless pass also any feeling of need to be concerned about the reasons that may have influenced these writers to treat their stimuli as they did.

2. The point to point investigation also has an important bearing on the question of stability of color tone. The results given in Part I make it easy to understand why it is not possible to find a red and a green stimulus that are invariable in color tone from the center to the periphery of the retina in all meridians. That is, the conception of a red and a green that are stable in tone presupposes a regularity in the relative rate of decrease in sensitivity to red and green on the one hand and to yellow on the other which the point to point investigation shows is very far removed from fact.

The claim to a stable red and a stable green was first made by Bull and later by Hess, Hegg and Baird in investigations of the relative limits of sensitivity to the paired colors. Working with pigment papers Bull added blue to his red and green stimuli in order that he might get colors that would not be sensed as yellowish in the peripheral retina.[1] His purpose in doing this, he states, was to find the physiologically pure red and green. Passing over the fact that the addition of blue in sufficient amounts to cancel the peripheral yellow gives an excess of blue in the more central portions of the retina (even outside of the macula) which is scarcely compatible with the tenet of introspective simplicity, this method of obtaining a stable red and green would presuppose, as we have already stated, a regularity in the relative rates of decrease of sensitivity to red and green on the one hand and to yellow on the other in the different meridians of the retina which is far removed from fact. For example, if the sensitivity to red fell off at the same rate in all meridians of the retina and the sensitivity to red and yellow in a constant ratio, the amount of blue which is required in a given meridian to neutralize the yellow component in sensation would suffice for this purpose in all meridians. Since neither of these essential conditions is present in the relative distribution of sensitivities from center to periphery of the retina in the different meridians, the futility of the search for the stable red and the stable green by the method proposed by Bull is

[1] Speaking of the gelatines used for his red stimulus, Baird (*op. cit.*, p. 60) says: "The red stimulus transmitted no part of the visible spectrum."

obvious. Moreover, it is perhaps just as obvious that stability of tone throughout the retina is by no means a necessary corollary of a four-color theory of the type proposed by Hering, and therefore that its use by the aforementioned writers for the purpose of searching out or isolating the four physiological processes was questionable even on *a priori* grounds. That is, the assumption that our color processes are conditioned by four physiological processes, the action of any one of which alone would give a sensation which is introspectively simple, should not by any means carry with it also the assumption that stimuli can be found to which one alone of these processes responds. For in the first place, such a narrowness of selectivity of response is not needed to explain our experience of the introspectively simple sensation; secondly, it is not as a general case characteristic of selectiveness of action; and thirdly, it is quite out of keeping with the change of tone of red and green in passing from the center to the periphery of the retina. The explanation of this phenomenon seems to have given not a little concern to the followers of the Hering theory who have apparently, in some cases at least, thought that if corresponding to the four simple sensations there are four simple physiological processes, it should be possible to find stimuli that would arouse one of these processes alone, which stimuli should of course be invariable in color tone for all parts of the retina. But, as we have already pointed out, this is neither a necessary nor perhaps even a plausible corollary of the fundamental assumption of four processes, the action of any one of which alone should give a simple sensation, and besides detracts needlessly from its explanatory value.

Hering's own criteria for the selection of the *Urfarben* were (1) introspective simplicity at or around the maximal saturation (**13**) and (2) following the lead of Fick, no change of color tone with change of intensity of the stimulus light (**14**). Whether or not constancy of tone can be expected for all intensities of light would again seem to depend on whether constant ratios of chromatic sensitivity obtain for all intensities of light; in other words, upon whether or not the select-

iveness of the chromatic response of the eye varies with the intensity of light, as does the achromatic response. If it does, it is too much to expect that this second criterion of Hering's will be of any especial service for the purpose for which he used it; for, depending upon the variations of ratio of sensitivity or relative amounts of the selectiveness of the chromatic response, one spectrum band may give the introspectively simple sensation at one intensity and a mixed sensation at a different intensity. Also the effect of the varying strength of the achromatic component on the color tone of the sensation aroused can not be left out of consideration. The attempt, therefore, to label, so to speak, the simple physiological process with a wave-length or spectrum specification, presupposes a simplicity in the eye's reactions which very probably does not exist. The investigation of the selectiveness of the chromatic response of the eye in relation to intensity of light is, as we have already stated, now in progress in this laboratory.

To explain the experience of introspectively simple red and green at the center of the retina and its change in tone in passing towards the periphery in terms of four physiological processes, the action of any one of which alone would give a simple sensation, it is necessary only to call attention to three factual considerations[1] the application of which to the point in ques-

[1] With regard to the first of these considerations it may be of interest to note that Hering did not himself seem to regard the simple physiological processes as narrowly selective in their response to wave-length, and that he recognized, implicitly at least, that all of the color processes exert an inhibitive action on each other. This conclusion may be derived from the following passages and from others in the article (15) from which they they are quoted: "Da alle sechs Processe fortwährend gleichzeitig, wenn auch mit sehr verschiedener Stärke in der Sehsubstanz stattfinden, so sind auch immer alle sechs Grundempfindungen, gleichzeitig gegeben. Jede Gesichtsempfindung ist daher eigentlich ein Gemisch aus den sechs Grundempfindungen, doch sind darin immer nur einige von den Grundempfindungen deutlich, die andern unter der Schwelle. Die Deutlichkeit, mit welcher die eine oder die andere der Grundempfindungen sich in der Gesammtempfindung zeigt, hängt von dem Verhältniss ab, in welchem die Stärke des, dieser Empfindung correlaten Processes zur Stärke der fünf übrigen steht. Ist z.B. der schwarze Process sehr stark im Vergleich zu allen andern, so tritt die schwarze Empfindung mit besonderer Deutlichkeit hervor, wobei die fünf übrigen so undeutlich werden können, dass sie nicht mehr einzeln wahrnehmbar oder, wie man zu pflegt, unter der Schwelle sind. Wir nennen dann die Gesammtempfindung schwarz. Sind z.B. die beiden Grundempfindungen Grün und Blau besonders deutlich, so nennen wir die Empfindung grünblau u.s.w. . . . "

tion apparently has not always been clearly kept in mind. (1) The selectiveness of the eye's response to wave-length is not complete. Apparently it ranges from a minimum to a maximum. In case of the red and yellow processes, for example, the maximum is reached respectively at certain points in the red and yellow portions of the spectrum and the minimum at a point in the orange. (2) There is an inhibitive action of the non-complementary colors[1] on each other as well as of the complementary colors. That is, the threshold of one of these colors in another is high and its value differs from color to color. And (3) the distribution of sensitivity is very irregular from point to point over the retina. That is, a certain range of wave-lengths in the red portion of the spectrum acting on the center of the retina arouses both the red and the yellow processes, the red strongly and the yellow weakly. The yellow does not come to sensation because it is below the threshold of yellow in red. When, however, the same stimulus acts on the peripheral retina at points where the red process is relatively undeveloped as compared with the yellow, the yellow is no longer subliminal in the red but becomes a component of the sensation of a value depending upon the ratio of sensitivity to red and yellow at the points in question, the

On pp. 79–81 he continues: "Ausser der weissen Valenz, welche allen Lichtstrahlen gemeinsam ist, kommen nun den einzelnen Strahlenarten verschiedene farbige Valenzen zu. Alle Strahlen von äussersten Roth oder vom *Anfange* des Spectrums bis zu jenem im Tone reinen Grün, welches eine Grundfarbe ist und welches wir das Urgrün nennen wollen, haben eine gelbe, alle Strahlen vom Urgrün bis zum violetten *Ende* des Spectrums eine blaue Valenz. Demnach theilen wir das Spectrum in eine *gelbwerthige* und eine *blauwerthige* Hälfte, wenn auch beide nicht gleich lang erschienen. Am Anfange des Spectrums ist die gelbe Empfindung so schwach, dass sie gegenüber der deutlicheren rothen unter der Schwelle bleibt; ebenso tritt sie in der Nähe des Urgrün wieder mehr und mehr hinter der grünen Empfindung zurück. Nur in einem schmalen Streifen erscheint uns das tonreine Gelb oder das Urgelb, welches der Grundfarbe entspricht. Analoges gilt vom Urblau, welches nach dem Urgrün hin immer mehr gegenüber der grünen Empfindung zurück tritt, nach dem Ende des Spectrums hin aber sich mehr und mehr mit rother Empfindung mischt.

[1] We do not wish to be understood as suggesting here that the inhibitive action of the non-complementary colors on each other requires the same mechanism for its explanation as the complementary or even that it takes place at the same functional level. We are inclined rather to believe that the inhibitive action of the achromatic on the chromatic excitation and possibly also of the non-complementary colors on each other takes place at a level posterior to the inhibiting action of the complementary colors.

mutually inhibitive actions of the excitations upon each other, etc. A similar explanation holds for the green. Why an analogous phenomenon of change of tone due to these factors should not occur in case of blue and yellow is obvious. That is, even though a subliminal red or green excitation were aroused in the center of the retina by the blue or yellow wave-lengths, it would become still more subliminal as the periphery of the retina is approached because of the more rapid decrease in sensitivity to red and green, and would not come to sensation. The changes that do take place in the color tone of yellow in passing from the center to the periphery of the retina we have already explained as an effect of the achromatic upon the chromatic component of the excitation. The demonstration of the validity of this explanation will be the work of a later paper.

Comments

The discussion relative to color theory, so far as we wish to consider theory at this time, may perhaps be summed up in the following comments.

1. An explanation of the color changes of red and green in passing from the center to the periphery of the retina may be found in three factual considerations: (*a*) the absence of complete selectivity of response of the eye to the red and green wave-lengths of light; (*b*) the inhibitive action of the non-complementary colors on each other; and (*c*) the relative distribution of sensitivity to red and green on the one hand and to yellow on the other in the periphery of the retina. The color tone of red and green seems to be very little dependent on the achromatic conditions of stimulation in any part of the retina.

2. The changes in the color tone of yellow (also of blue, so far as they occur), in passing from the center to the periphery of the retina seem to be largely, if not entirely, an effect of the achromatic conditions,—in physiological terms an effect of the achromatic upon the chromatic component of the excitation, the state of achromatic adaptation of the eye, etc. Of the four principal colors, the color tone of blue and yellow is as a general case the most dependent on the

achromatic conditions. Moreover, given the same achromatic conditions there is a striking agreement in the effect in all parts of the retina. The relative distribution of chromatic sensitivities apparently plays little if any part in the changes of color tone of blue and yellow in passing from the center to the periphery of the retina.

3. The claim that a red, green, blue, and yellow stimulus may be found to which the eye will give a response invariable in color tone in all parts of the retina is based on a very incomplete and inadequate investigation of the eye's possibilities of response. Also the importance of the bearing of such a possibility on color theory seems to the present writers in many instances at least to have been very wrongly stressed. (Our own conclusions with regard to the possibility of obtaining stability of tone for these colors, for example, are based on a very minute investigation on a number of observers in sixteen meridians of the retina. Moreover, some of the more important findings of this investigation have been confirmed year by year in the work of the undergraduate laboratory.)

4. There is no basis of fact for a claim that a constant ratio of sensitivity to the pairs of colors red and green, and blue and yellow obtains in all parts of the retina; nor is it apparent that such a claim is of any considerable consequence to the fundamental postulates of theories of the Hering type. It is more important, for example, (*a*) that wherever one of these pairs of processes be found, the other shall also be found; and (*b*) that a constancy of ratio of cancelling proportions for the pairs of colors obtains in all parts of the retina. (The power to arouse sensation and the power to cancel the antagonistic or complementary color are not, as we have already shown, equivalent.) With regard to the first of these points it does seem to be of rather serious consequence that we have not been able to get even approximately coextensive zones of sensitivity to red and green, for we have no means of knowing where the color sensing substances are except by the responses aroused. With intensive stimuli, it will be remembered, we have found the limits of sensitivity to red, blue, and yellow to

coincide with the limits of white light vision, but the limits of sensitivity to green fall far short of this even with the greatest spectrum intensities we have as yet been able to obtain.

5. The constancy in the cancelling proportions of the paired colors from center to periphery of the retina in all meridians as contrasted with the great irregularity in the distribution of sensitivity, obviously presents a problem to theories of the Hering type; for while there is not and should not necessarily be in terms of theory an equivalence in the power to arouse sensation and to cancel the complementary color, some degree of constancy of relation between the two functions might be expected. Perhaps the easiest solution is to be found in the conception that more than one level of activity is involved in the process of arousing sensation and that the locus of the deficiencies which cause the irregularity in the distribution of sensitivity to the paired colors is posterior to the level at which the cancelling action takes place. While an explanation of this type meets with less inertia of acceptance, perhaps, for the occasional and sporadic deficiency such as the small areas of the Schumann type in the peripheral retina (**16**), than for deficiencies and anomalies of the order of magnitude here considered, still the need for it or some similar concept to explain these anomalies and deficiencies is no less insistent. Even the extensive deficiency in the sensitivity to green noted above is contradictory to the concept of paired processes only on the assumption that the deficiencies which affect sensitivity may occur at only one functional level; for again it may be that the deficiencies which prevent the green stimulus from arousing sensation are posterior to the level of the cancelling action. If this were true, the cancelling proportions between the paired colors could be constant from the center to the periphery of the retina even though the sensitivity to one of the colors had fallen off a great deal or disappeared entirely, as seems to be the case when either a partial or full spectrum gray is sensed as colorless from the center to the periphery of the retina without any change in the composition of the stimulus to compensate for the extensive deviation from regularity in

the distribution of sensitivities. As in the previous paper, however, our comments with reference to theory are meant to be only tentative and suggestive (**17**). Our purpose has been primarily to call attention to the lack of adequate explanatory concepts to meet the needs of our growing knowledge of the visual phenomena. Theories whose especial fitness is for the explanation of the fundamental facts of positive sensation, the after-image, and contrast can scarcely be considered as final and complete.

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THE ABSOLUTE LIMITS OF COLOR SENSITIVITY AND THE EFFECT OF INTENSITY OF LIGHT ON THE APPARENT LIMITS

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Introduction

In describing a general plan of investigating the chromatic sensitivity of the peripheral retina in an earlier paper (1) the following were mentioned as two of the problems which we wished to take up: (*a*) a point to point determination of comparative sensitivities to the different colors from the center to the periphery, and (*b*) an investigation of the limits of sensitivity. The former of these problems has been made the subject of a recent paper (2). The latter will be treated of here.

The investigation of the limits of sensitivity may be considered from two points of view. As indicated in the first of the papers referred to above, (*a*) it may be made a part of the investigation of the comparative sensitivities of the peripheral retina to the different colors; and (*b*) it may be considered more specifically in relation to points of theory. In the former case the limits should be obtained with stimuli equalized in energy. The results will then represent positions on the retina at which the stimuli for one of the intensities which it is possible to employ have the same or nearly the same threshold value.[1] In the latter case the problem con-

[1] Strictly speaking the threshold value may be considerably less at this point than the intensity of the stimulus employed, because the stimulus may be increased much above the threshold value in the far periphery of the retina without changing the limits by a detectable amount. That is, the stimulus value of the just noticeable

sidered in relation to its historical development divides into two,—a determination of the relative or apparent limits and a determination of the absolute limits. In the second of the papers referred to above it was shown that the determination of the apparent limits was given an undue importance in relation to theory by Hess and his followers because of their failure to realize that great irregularity and not uniformity characterizes the decrease of sensitivity from the center to the periphery of the retina. The details of that demonstration need not be repeated here. The determination of the absolute limits of sensitivity, however, does sustain an important relation to theory, especially to theories of the paired process type; for if it be found that sensation can be aroused farther out from the center of the retina for one of the paired colors than for the other, that fact must tell against the theory unless some supplementary concept is provided to explain the discrepancy. For one thing we have undertaken, therefore, to determine the limits of sensitivity with stimuli any further increase in the intensity of which tends to decrease rather than to increase the chromatic component of the response. For another we have determined the effect of a given range of variation of intensities on the apparent limits. Our reason in part for doing this was to supplement at higher intensities the work of former papers (**3**) in which we called attention to the large variations that are required in any of the factors influencing the chromatic response (intensity being the most effective of these) to change the limits of sensitivity as much as 1 degree especially when a certain degree of excentricity has been reached, pointing out in particular with regard to the work of previous writers, (*a*) the importance of taking into account deviations of 1–3 degrees from coincidence of limits when conclusions with regard to comparative sensitivities are to be drawn from the results, and (*b*) the futility of making a brightness equalization of the stimuli, with its attendant disadvantages,

difference in limits is much greater than the stimulus value of the difference limen of intensity. In other words, a given point in the peripheral retina may be considered the limit for a range of stimulus intensities, varying in magnitude with its degree of excentricity.

for the determination of the limits with lights of medium and high intensities and perhaps for any but intensities so low as to give very narrow limits. For the latter point three reasons may be given. (1) The brightness equation does not equalize the stimuli in power to arouse the chromatic response, the only subjective equation, so far as we can see, that could rightly be given a place in a determination of the limits of chromatic sensitivity, and this only in a determination of whether or not the same ratio of sensitivity holds for the limits as for the center or other point at which the equation was made. (2) It does not equate them in intensity (the equation is merely of the very selective achromatic response to the stimuli). And (3) so far as the effect of the achromatic on the chromatic component of the excitation is concerned (the final variable that might be considered), it has already been shown by one of the writers in a previous paper (4) that there is not enough of this effect for the colors ordinarily used to change the limits by a detectable amount. The particular bearing of the present work on this question is to give a clearer and more definite idea of just how much difference in intensity or equivalent influence is required to change the limits by detectable amounts in the mid and far periphery of the retina. In the beginning this was in fact our chief incentive to undertake the work.

The Problem

The investigation was given the following form. (1) An attempt was made to find out whether by means of our spectroscopic apparatus, which was designed especially to give high intensities of light, stimuli could be obtained which could be sensed as color to the limits of white light vision. (2) The effect on the extension of the limits of sensitivity of varying the stimuli through quite a wide range of intensities was investigated. And (3) the determination of the limits was made in 16 meridians with all of the lights made equal in energy to the blue of the prismatic spectrum employed and with 1/32 of this amount of energy.

Conditions under which the work was done

The conditions under which the work was done fall under five headings: (1) the wave-lengths of light employed and the means used of getting greater purity of light than is found in the prismatic spectrum; (2) the energy content of the stimuli used and the method of measurement; (3) the control of the brightness of preëxposure and surrounding field; (4) the control of the general illumination of the optics room; and (5) the method of rendering the amount of light entering the eye independent of variations in the size of the pupil, without the use of an artificial pupil. These conditions are so nearly identical with those used in the work of the immediately preceding papers that at the request of the Editor space has not been taken for their repetition in the present paper. For a description of the conditions the reader is referred to 'Chromatic Thresholds of Sensation and their Bearing on Color Theory, Part I.,' this journal, 1919, **26**, pp. 18–25.

The stimulus used was the circular aperture of the campimeter, 15 mm. in diameter, filled with light by the focusing lens. At a distance of 25 cm. from the pupil of the eye, on which the light from the objective slit of the spectroscope was focussed, this aperture subtended a visual angle of 3° 26′. The time of exposure was 1 sec. and the interval between exposures varied between 3–5 min. depending on circumstances and the need for precautionary measures. If the stimulus was sensed in its proper color at any time during the 1 sec. interval of exposure, the retina was called color sensitive at that point. (At the limits of white light vision the red stimulus, for example, of the intensity used was sensed as a tint of red.) The field in the 16 meridians was always mapped for one color before the work on another color was begun.

Systematic results were obtained for all of the points of the work for only one observer. This was the observer whose results were published in the immediately preceding papers: 'Chromatic Thresholds, etc., Parts I. and II.' For data with regard to the various ways in which the normality of both the chromatic and achromatic sensitivity of this observer,

central retina, and chromatic sensitivity, peripheral retina, has been confirmed, the reader is referred to pp. 26–32 of the first of the papers noted above. Data on additional points, important in a general specification of the ocular condition of the observer, have also been published in various places: *e.g.*, on the dioptric or refraction condition and power to sustain acuity in *Trans. Illum. Eng. Soc.*, 1915, **10**, p. 1128, and in other papers by us on lighting in relation to the eye; on muscle strength, muscle balance, muscle lag, photopic acuity, near point, range of accommodation, and refraction condition (more recent), *Trans. Amer. Ophthal. Soc.*, 1918, **66**, pp. 142–163; and on scotopic acuity and amount and rapidity of scotopic adaptation, *Trans. Amer. Ophthal. Soc.*, 1919, **67** (in press). The more important points such as the coincidence of the limits of red, yellow and blue with the limits of white light vision; the narrower limits for green; the interlacing of limits for stimuli of medium intensity of equal energy, or of the same general order of intensity; and the large differences in amount of light required to change the limits of sensitivity by a detectable amount in the mid and far peripheral portions of the retina, have been confirmed in a less detailed and systematic way by one or more check observers.

Results

The following results were obtained. (1) It was quite easy to obtain an intensity of light for the red, yellow and blue wave-lengths that could be sensed to the limits of white light vision. In fact these wave-lengths in the spectrum employed were considerably above the threshold at the limits of white light vision in the sixteen meridians investigated. The limits of the green of this spectrum, however, fell far short of the limits for white light; nor could the zone of sensitivity be widened as much as 1 degree by increasing the current in the Nernst filament from 0.6 to 0.8 ampere. The energy entering the eye from the spectrum of the Nernst filament operated by 0.6 ampere of current with the width of collimator slit employed was for the red 9096.639×10^{-10}

watt; for the yellow, 4065.624×10^{-10} watt; for the green, 1562.388×10^{-10} watt; and for the blue, 882.025×10^{-10} watt. The energy value of the threshold at the limits of white light vision in the nasal meridian, for example, was for the red 277.836×10^{-10} watt; for the yellow, 268.95×10^{-10} watt; and for the blue, 264.368×10^{-10} watt. The intensity of light for these colors in the 0.6 ampere spectrum was, therefore, strongly supra-liminal at the limits of white light vision, as is stated above. In the 0.6 ampere spectrum, the energy of the green light, it will be noted, was greater than the energy of the blue, but less than the energy of the red and yellow. It was, however, nearly six times as great as the threshold value of these colors at the limits of white light vision. Moreover, when the current was raised to 0.8 ampere this value was considerably increased, but there was still no detectable extension of the limits. Since then the sensitivity to green at the center of the retina and for several degrees towards the periphery is approximately the same as to blue and considerably greater than to red and to yellow, and since so large an increase in the energy value of the stimulus made no detectable difference in the limits and any further increase lessened rather than increased the chromatic component of the response, it seems highly improbable that the limits could by any means whatsoever be extended the 20–35 degrees needed to make them coextensive with the limits of white light vision. It seems fairly certain, therefore, that while the far periphery of the retina is only deficient in its chromatic sensitivity to red, yellow and blue, the blindness to green for the observers used is absolute.

(2) In the investigation of the effect of changes of intensity on the limits of sensitivity eight intensities were used, sustaining to each other the following relations: 1, 1/2, 1/4, 1/8, 1/16, 1/32, 1/64 and 1/128. The highest intensities were taken respectively from the prismatic spectrum of a Nernst filament operated by 0.6 ampere of current and from a spectrum made equal in energy to the blue of this spectrum. These spectra will be designated as Spectrum

A and Spectrum B. The reductions were produced by means of an aluminum sectored disc of 180, 90, 45, etc., degrees open sector. The energy values of the different intensities of light, as has already been stated, were obtained by radiometering the highest intensities and computing the lower from the simple law of the disc. It had been our intention to make the investigation systematically with the eight different intensities in the sixteen meridians of the retina. However, for the purpose of the present paper a briefer substitute plan has been adopted. A preliminary investigation was made with the eight intensities of Spectrum A in two meridians of the retina, the nasal and the temporal, which meridians represent opposite extremes with regard to breadth of zone of sensitivity, in order to get some idea of the amounts of reduction that would be needed to be effective in changing the limits. It was found, for example, that a reduction of the red light to 1/32 of its value at intensity A was not sufficient to narrow the limits in the nasal and temporal meridians, the meridians designated in the tables and charts as 90 degrees. At this value the stimulus was still slightly supra-liminal in these meridians at the limits of white light vision. This amount of reduction, however, was sufficient to narrow the limits for the other stimuli by quite considerable amounts. Also a further investigation showed that it was enough to narrow the limits for red in 12 out of the 16 meridians employed. It was decided, therefore, to make the final determinations in the 16 meridians with the full intensities A and B and with 1/32 A and B. The amount of narrowing for the yellow of the prismatic spectrum in the different meridians produced by this reduction ranged from 3–11 degrees; for the green from 5–17 degrees; for the blue, from 10–18 degrees; and for the red, from 0–8 degrees. For the equal energy spectrum the amount of narrowing for the yellow ranged from 5–18 degrees; for the green, from 5–15 degrees; for the blue, from 4–18 degrees; and for the red from 3–25 degrees.

(3) In case of the equal energy spectrum of the higher intensity, all of the lights with the exception of the green

were seen in their proper color to the limits of white light vision in each of the 16 meridians. Made equal in energy to the blue of the prismatic spectrum (882.025×10^{-10} watt) the red and yellow were considerably less in energy value than was the green of the prismatic spectrum, still the red and yellow were sensed to the limits of white light vision while the green which represented a considerably greater amount of energy fell short of those limits by amounts varying from 20–35 degrees in the different meridians. There can be no reasonable doubt, we believe, that the difference found here represents an actual difference in sensitivity. It obviously can not be attributed to the relative intensities of the stimuli employed.

Landolt has also investigated the effect of high intensities on the extension of the limits of sensitivity. Writing of this work (**5**), he says: "In ein absolut dunkles Zimmer fiel nur durch eine kleine Öffnung im Finsterladen directes Sonnenlicht. Dieses wurde auf das äusserste Ende des Perimeterbogens gelenkt. Während wir unser Auge ins Centrum des Bogens setzen, bracht man in die kleine, intensive beleuchtete Stelle farbige Papiere von möglichster Intensität der Färbung. Nun bewegtet sich das Auge langsam vom entgegengesetzen Ende des Bogens nach Scheitelpunkte zu und es zeigte sich dabei, dass wenigstens mit der innern Netzhautpartie alle Farben schon bei 90° erkannt wurden. Die Grösse des Objectes betrug weniger als 1 cm².

"Als dieselben Prüfungen auch mit Spectralfarben zu machen, entwarfen wir ein Sonnenspectrum im sonst dunkeln Zimmer und liessen es durch eine achromatische Linse auf einen Ende des Perimeters befindlichen Schirm fallen. Dieser hatte eine verändliche Spalte, mittelst welcher man die einzelnen Farben aus dem Spectrum isolieren konnte. Während wir nun wiederum nach langer Adaptation, und bei verbundenem zweiten Auge das eine Ende des Bogens fixierten, würde von einem Assistenten irgendeine Farbe des Spectrums auf die Spalte gelenkt, und wir drehten nun, unter stehter Fixation unserer Fingerspitze, welche sich auf dem Bogen bewegte, das Auge allmählig der Farbe entgegen.

Es zeigte sich auch hier wiederum dass alle Farbe schon bei 90° erkannt werden, wenn sie intensiv genug sind."

Landolt's investigation was made, it will be noted, in a dark room while ours was made in a light room. We have

Table I

A. The Effect of Intensity of Stimulus on the Limits of Sensitivity, Prismatic Spectrum

In this table are given the results of a preliminary investigation in two representative meridians to show how much reduction is needed to produce a significant change in the limits of sensitivity. Eight intensities of stimulus were used: A, 1/2A, 1/4A, 1/8A, etc.

Meridian Investigated	Stimulus	Limits of Sensitivity for							
		Intensity A	Intensity ½A	Intensity ¼A	Intensity ⅛A	Intensity $\frac{1}{16}$A	Intensity $\frac{1}{32}$A	Intensity $\frac{1}{64}$A	Intensity $\frac{1}{128}$A
Nasal........	Red (670 μμ)	92	92	92	92	92	92	88	86
	Yellow (581 μμ)	92	92	92	92	91	89	88	88
	Green (522 μμ)	69	69	69	66	63	62	59	56
	Blue (468 μμ)	92	92	87	83	79	78	77	76
Temporal.....	Red (670 μμ)	61	61	61	61	61	61	46	44
	Yellow (581 μμ)	61	61	61	61	55	47	46	45
	Green (522 μμ)	45	45	45	42	34.5	32.5	30	29
	Blue (468 μμ)	61	61	56	45	43.5	43	43	43

B. The Energy Values of the Stimuli Used

Total energy of light at campimeter opening and at eye

(watt $\times$ 10^{-10})

Intensity	Red (670μμ)	Yellow (581μμ)	Green (522μμ)	Blue (468μμ)
A[1]	9096.639	4065.624	1562.388	882.025

[1] The energy values of 1/2, 1/4, 1/8, 1/16, 1/32, 1/64 and 1/128 A may be obtained by dividing the above values by the appropriate factor.

The energy density at the campimeter opening (watt per sq. mm.) may be obtained by multiplying the above values by 0.005659; the energy density at the eye, by multiplying them by 0.303.

not as yet had opportunity to repeat the work of the present paper with the dark adapted eye. However, determinations somewhat rougher and less detailed than those described

here have sufficed to show that for our observers the far periphery of the retina is color-blind to green also with the dark adapted eye. With reference to the relative insensitivity of the peripheral retina to green, it may further be noted that in our results with the Hering papers with a different set of observers the limits for green fell much nearer to the center of the retina than for red, yellow and blue. The results represented in Fig. 5, for example, were taken from this series of observations. That the limits for green are narrower than for red, yellow and blue with stimuli of the same order of intensity has, moreover, been verified many times in the work of our undergraduate laboratory.

In Table I., A, are given the results of the preliminary investigation in the nasal and temporal meridians to find out whether an intensity of light may not be gotten sufficiently high to make the limits of color sensitivity coincide with the limits of white light vision, and once this intensity is attained how much reduction is needed to produce a significant narrowing of the limits. We have already indicated in this and in previous papers the large changes of intensity that are needed to change the limits by a significant amount when a certain degree of excentricity has been reached. How very large these changes have to be for the far periphery of the retina is shown in this table.

In Table I., B, is given a specification of the energy values of the stimuli used in making the determinations represented in Table I., A. Four energy values may perhaps be considered of importance for each determination: The total value at the campimeter opening, the density per sq. mm. at the campimeter opening, the total energy entering the eye, and the density per sq. mm. at the eye. For the sake of brevity, however, only one of these values is given in the table, namely, the total energy entering the eye; and the factors needed to convert this value into density at the eye and at the campimeter opening are appended in a footnote. Since all of the light from the campimeter opening is focused into the image on the pupil, the figures expressing the total energy at the eye and at the campimeter opening are the same.

The most important of the four specifications noted are probably the total amount of light entering the eye and the density at the campimeter opening. The latter value, for example, sustains a fixed but unknown ratio to the density of the image formed on the retina.

Table II

The Brightness Values of Preëxposure and Surrounding Field

In this table are given the brightness values of preëxposure and campimeter screen in candlepower per square inch[1] for the determination of limits given in Table I. In all cases in which it was possible the brightness of the preëxposure and campimeter screen was made equal to that of the stimulus at the limits of sensitivity.

Meridian	Stimulus	Brightness Value of Preëxposure and Campimeter Screen for							
		Intensity A	Intensity ½A	Intensity ¼A	Intensity ⅛A	Intensity $\frac{1}{16}$A	Intensity $\frac{1}{32}$A	Intensity $\frac{1}{64}$ A	Intensity $\frac{1}{128}$ A
Nasal....	Red (670 $\mu\mu$)	0.05088	0.05088	0.05088	0.05088	0.05088	0.05088	0.03093	0.02116
	Yellow (581 $\mu\mu$)	0.05088	0.05088	0.05088	0.05088	0.05088	0.05088	0.03663	0.02686
	Green (522 $\mu\mu$)	0.05088	0.05088	0.05088	0.03663	0.03663	0.02686	0.02116	0.01384
	Blue (468 $\mu\mu$)	0.05088	0.05088	0.03663	0.02686	0.01262	0.01140	0.00643	0.00578
Temporal	Red (670 $\mu\mu$)	0.05088	0.05088	0.05088	0.05088	0.05088	0.05088	0.03093	0.01791
	Yellow (581 $\mu\mu$)	0.05088	0.05088	0.05088	0.05088	0.05088	0.05088	0.02686	0.02116
	Green (522 $\mu\mu$)	0.05088	0.05088	0.05088	0.03663	0.02686	0.01384	0.01140	0.01140
	Blue (468 $\mu\mu$)	0.05088	0.05088	0.03663	0.03093	0.01262	0.01140	0.00716	0.00643

In Table II. are given the brightness values of the preexposure and campimeter screen for the work represented in Table I. As stated earlier in the paper the preëxposure and the campimeter screen were selected from the Hering series of standard papers. In case of the higher intensities of light used, No. I of this series (the standard white, coefficient of reflection about 75 per cent.) reflecting the light of the room was not as bright as the stimulus light. These cases may be identified in this and the following tables by the brightness value of this paper under the illumination of the room, namely, 0.05088 cp. per sq. in.

[1] The above values may be converted into millilamberts by multiplying by 486.8.

In Table III. are given the limits of sensitivity in 16 meridians of the retina for the highest intensity of light used for the work of Table I., intensity A, and for 1/32 A, an intensity representing the order of reduction needed for all of the colors to produce any considerable narrowing of the

Table III

The Effect of Intensity of Stimulus on the Limits of Sensitivity, Prismatic Spectrum

In this table are given the limits of sensitivity in 16 meridians of the retina for intensity A and 1/32A of Table II. The upper vertical meridian is numbered 0° and the lower vertical 180°. Reading down to right or left they are 25°, 45°, 70°, 90°, 110°, 135°, 155°, and 180°.

Meridian Investigated		Limits of Sensitivity for							
		Intensity A				Intensity 1/32A			
		Red ($670\mu\mu$)	Yellow ($581\mu\mu$)	Green ($522\mu\mu$)	Blue ($468\mu\mu$)	Red ($670\mu\mu$)	Yellow ($581\mu\mu$)	Green ($522\mu\mu$)	Blue ($468\mu\mu$)
	0°	65	65	36	65	64	57	29	50
Nasal	25°	86	86	49	86	83	79	36	72
	45°	90	90	52	90	89	83	38	76
	70°	92	92	67	92	92	86	59	77
	90°	92	92	69	92	92	89	62	78
	110°	91	91	68	91	90	87	59	78
	135°	88	88	61	88	87	84	49	75
	155°	86	86	47	86	84	78	35	67
	180°	57	57	36	57	53	47	27	42
Temporal	25°	65	65	44	65	64	55	31	52
	45°	65	65	50	65	57	56	33	51
	70°	62	62	46	62	55	50	35	44
	90°	61	61	45	61	61	47	32.5	43
	110°	58	58	37	58	57	49	31	48
	135°	55	55	32	55	55	48	27	20
	155°	54	54	30	64	50	43	25	41

limits at the extreme periphery of the retina. The 16 meridians used are designated as follows. The upper vertical meridian is marked 0 and the lower vertical 180 degrees. Beginning with 0 and reading down to left or right they are 0, 25, 45, 75, 90, 110, 135 and 180 degrees. The specification of the energy of the stimuli at intensity A and 1/32 A is given, it will be noted, in Table I., B. For all of the stimuli at intensity A, No. 1 of the Hering series of papers was used as preëxposure and campimeter screen, as has already been noted. This paper illuminated by the light of the room was too dark (0.05088 cp. per sq. in.) for all of the four colors at the

limits of sensitivity. However, for the want of a suitable pigment surface of higher reflection coefficient it was used. For intensity 1/32 A, it was darker than the yellow stimulus

Table IV

A. The Effect of Intensity of Stimulus on the Limits of Sensitivity, Equal Energy Spectrum

In this table are given the limits of sensitivity in 16 meridians of the retina for stimuli all made approximately equal in energy to the blue of the prismatic spectrum used in Table I., and for 1/32 of this intensity,—intensity B and 1/32 B.

Meridian Investigated		Limits of Sensitivity for							
		Intensity B				Intensity $\frac{1}{32}$B			
		Red (670μμ)	Yellow (581μμ)	Green (522μμ)	Blue (468μμ)	Red (670μμ)	Yellow (581μμ)	Green (522μμ)	Blue (468μμ)
	0°	65	65	34	65	62	56	29	50
Nasal	25°	86	86	47	86	74	70	34	72
	45°	90	90	50	90	74	78	36	76
	70°	92	92	63	92	78	85	50	77
	90°	92	92	69	92	81	87	59	78
	110°	91	91	64	91	79	85	58	78
	135°	88	88	44	88	74	80	42	75
	155°	86	86	36	86	61	74	32	67
	180°	57	57	31	57	46	39	25	42
Temporal	25°	65	65	39	65	57	54	30	52
	45°	65	65	39	65	47	55	32	51
	70°	62	62	42	62	46	48	30	44
	90°	61	61	41	61	40	45	30	43
	110°	58	58	36	58	45	45	29	48
	135°	55	55	28	55	49	41	25	40
	155°	54	54	26	54	47	38	24	41

B. The Energy Values of the Stimuli Used.

Total energy of light at campimeter and at eye (watt $\times 10^{-10}$)

Intensity	Red (670 μμ)	Yellow (581 μμ)	Green (522 μμ)	Blue (468 μμ)
B[1]	891.050	882.510	884.946	882.025

and approximately equal to the green and red. For the blue stimulus Nos. 9–14 of the Hering series (0.01404–0.0114 cp. per sq. in.) were used as needed in the different meridians. The photometric values for these intensities and intensity

[1] The energy value of 1/32 B may be obtained by dividing the above values by the appropriate factor.

The energy density at the campimeter opening (watt per sq. mm.) may be obtained by multiplying the above values by 0.005659; the energy density at the eye, by multiplying them by 0.303.

B and 1/32 B have not been given in detailed tabular form because of the large number of repetitions that occur.

In Table IV., A, are given the limits of sensitivity in 16 meridians of the retina for the four stimuli all made equal in energy to the blue used in Table I. and for 1/32 of this value. These values are, as we have already indicated, designated in

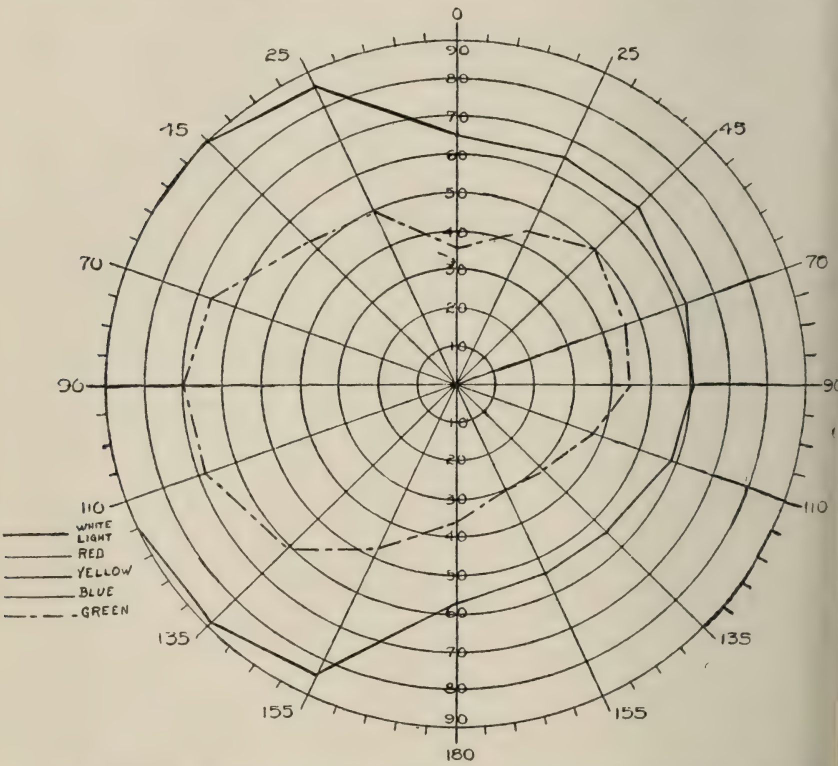

FIG. 1. The effect of intensity of stimulus on the limits of sensitivity, prismatic spectrum. In this chart are represented the limits of sensitivity for intensity A of Table I.: red 9096.639, yellow 4065.624, green 1562.388, and blue 882.025 watt × 10^{-10}.

the table as intensity B and 1/32 B. In Table IV., B, are given the energy values of the stimuli used for Table IV., A. For the higher intensity of these stimuli, intensity B, No. 1 of the Hering series of papers (0.05088 cp. per sq. in.) was used for the preëxposure and campimeter screen. Again it was darker than all of the four colors at the limits of sensitivity. For intensity 1/32 B it was slightly darker than the yellow.

For the green of this intensity the no. 2 gray of this series was used (0.0366 cp. per sq. in.); for the red nos. 10–14 (0.01384–0.0114 cp. per sq. in.) varying for the different meridians; and for the blue, nos. 7–14 (0.01791–0.0114 cp. per sq. in.).

A graphic representation of the results of Table III. is given in Figs. 1 and 2. In Fig. 1 are shown the limits of

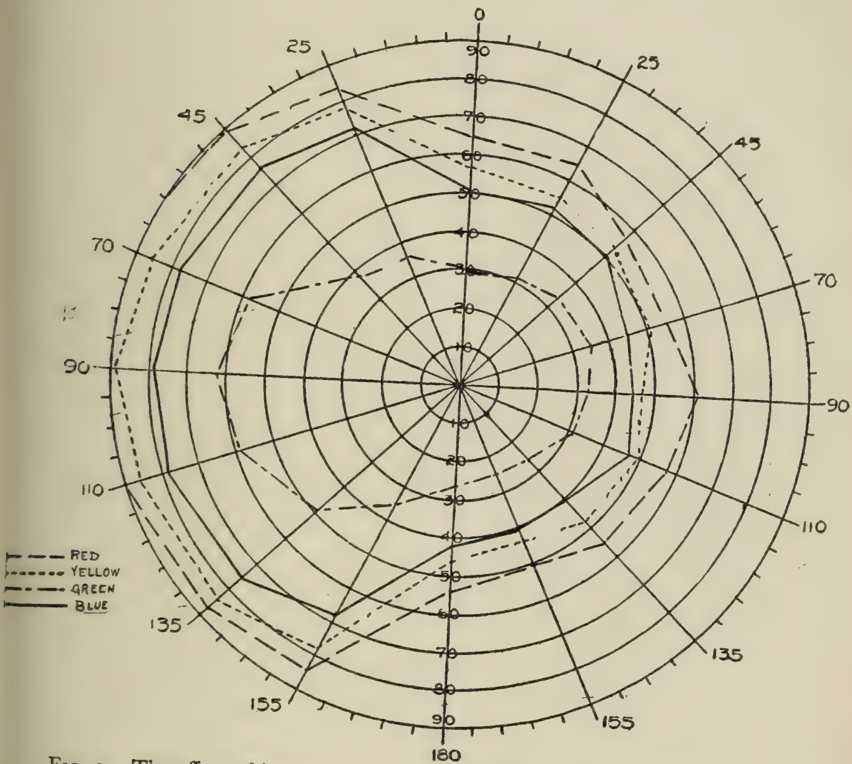

FIG. 2. The effect of intensity of stimulus on the limits of sensitivity, prismatic spectrum. In this chart are represented the limits of sensitivity for intensity 1/32 A of Table I.: red 284.27, yellow 127.051, green 48.825, and blue 27.563 watt $\times$ 10^{-10}

sensitivity to the four stimuli in the 16 meridians for the intensities represented in the prismatic spectrum *A*. The limits for the red, yellow and blue stimuli at this intensity are, it will be remembered, coincident with the limits of white light vision. All four limits may be represented, therefore, by a single tracing, an unbroken line in black. The limits for green are represented by a broken line. In Fig. 2 are

represented the limits of sensitivity for the four stimuli at the intensities represented in the prismatic spectrum, 1/32 A. In this case the zone of sensitivity to blue is outlined by an unbroken line and the zones for the other colors by broken lines as indicated in the figure. An inspection of this figure will show that the degree of excentricity of the limits is in the order of the intensity of the stimuli. In discussing the

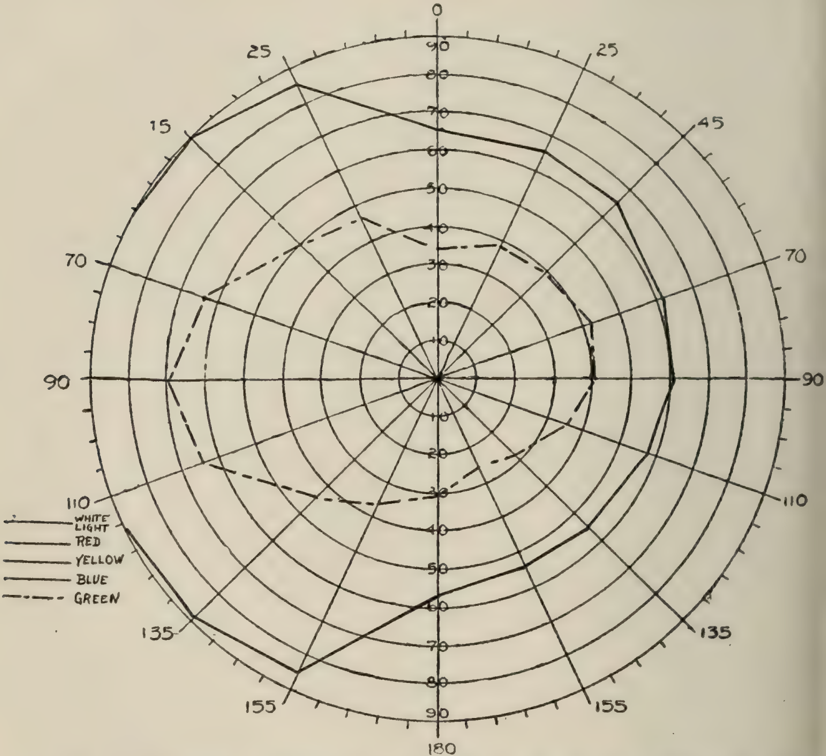

FIG. 3. The effect of intensity of stimulus on the limits of sensitivity, equal energy spectrum. In this chart are represented the limits of sensitivity for intensity B of Table IV.: red 891.05, yellow 882.51, green 884.946 and blue 882.025 watt $\times 10^{-10}$.

significance of the crisscrossing or interlacing of the limits obtained with the Hering pigment papers in previous work, this is what was pointed out would occur if there were a significant difference in the intensity of the stimuli. That is, if the zone of sensitivity to red, for example, is in one meridian wider and in another narrower than to green, etc., it can not

be due to any difference in the intensity of the stimuli; for such a difference, if significant, would make one zone consistently wider or narrower than the other in all meridians.

A graphic representation of the results of Table IV. is given in Figs. 3 and 4. In Fig. 3 are shown the limits of sensitivity to the four stimuli in the 16 meridians for the intensities represented in the equal energy spectrum *B*.

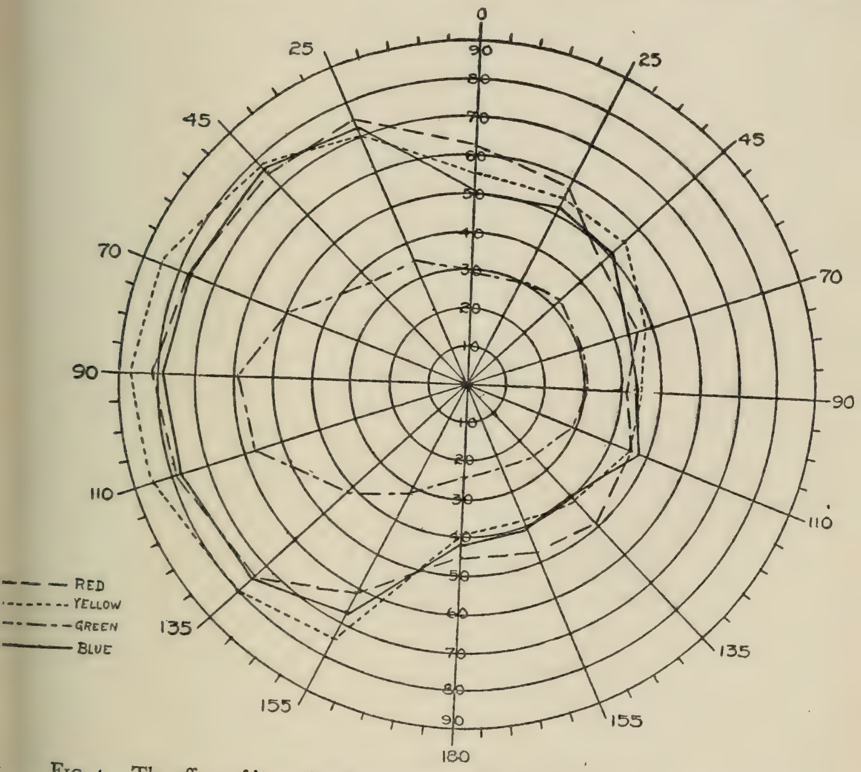

FIG. 4. The effect of intensity of stimulus on the limits of sensitivity, equal energy spectrum. In this table are represented the limits of sensitivity for intensity 1/32 B of Table IV.: red 27.845, yellow 27.578, green 27.655, and blue 27.563 watt $\times 10^{-10}$.

Again the limits for the red, yellow and blue stimuli coincide with the limits of white light vision and are represented by a single tracing, the unbroken line in black. The limits for green are represented by a broken line. In Fig. 4 are shown the limits for the four stimuli at the intensities represented in the equal energy spectrum 1/32 B. With regard to this

figure the following points may be noted. (1) With stimuli of equal energy the limits of no one of the colors, red, yellow and blue, are consistently wider than the others. That is, their limits are characterized by frequent crisscrossing or interlacing. The limits for all three colors, however, are consistently wider than for green. And (2) Fig. 4 sustains a

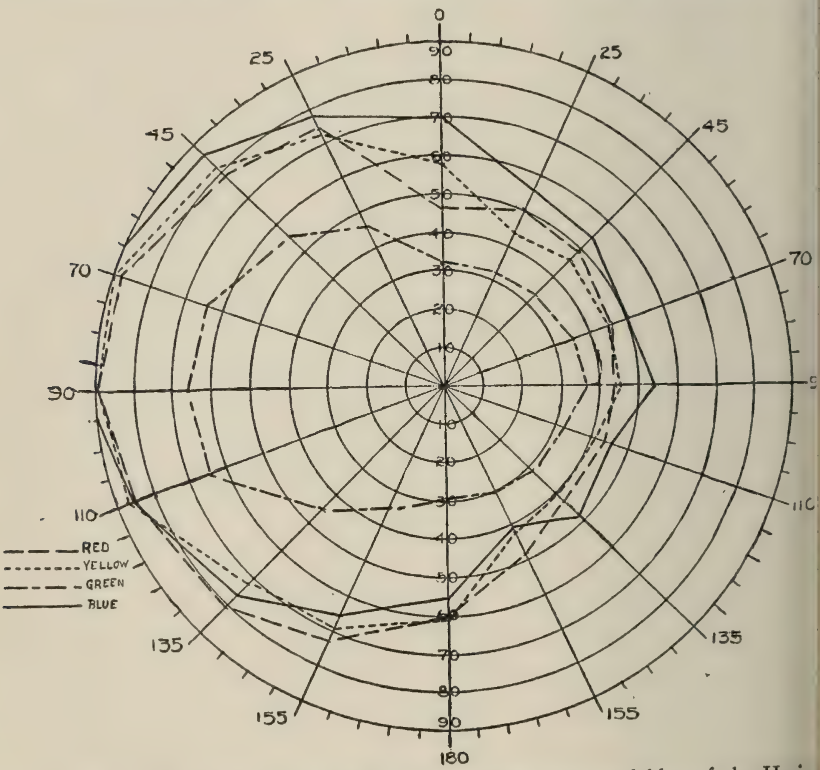

FIG. 5. The limits of sensitivity to red, yellow, green and blue of the Herin series of pigment papers, intensity of illumination, vertical component, 390 foot-candles

somewhat striking general similarity to the charts obtained for the Hering pigment papers. One of these showing the limits with a surrounding field and preëxposure of the brightness of the colors employed is given in Fig. 5. While no conclusion can be drawn from this similarity with regard to the relative energies of the wave-lengths dominantly reflected by these papers; still it suggests that they may all, roughly speaking, be somewhere near the same order of value, a

least much more nearly so than are these colors in the prismatic spectrum. The red, yellow, green and blue of the prismatic spectrum gave, it will be remembered, rather widely concentric, not crisscrossing limits.

In this general connection it may be of interest also to note the close correlation which obtains between the results of this investigation and those of the previous investigation of the sensitivity of the peripheral retina by the threshold method. That is, wherever the thresholds are found to be low the limits are found to be wide, and conversely wherever the thresholds are high the limits are found to be correspondingly narrow. Some interesting results follow from this. For example, in a given meridian the threshold curve for a given color is found to be very irregular, rising in some places slowly, in others quickly, and still in others dropping and rising again. These fluctuations in the curve are, moreover, different in the different meridians. This means, of course, that the shape of the zones of sensitivity for this color should change with the intensity of the stimulus employed, which is found to be the case. Furthermore, in the same meridian the threshold curves for the different colors differ from each other widely in the direction and amount of the irregularity: and this difference in turn varies from meridian to meridian. The result of this is that a crisscrossing or interlacing of limits must take place whenever stimuli of such relative intensities are used that the limits are of the same general order of excentricity. In other words, as was pointed out in our discussion of this phenomenon in earlier papers, crisscrossing can mean only that there is a lack of uniformity in the relative sensitivity to the different colors in the different meridians. For example, when it occurs in the limits for blue and yellow, it indicates that the ratio of sensitivity to blue and yellow changes in passing from meridian to meridian. In short any investigation at all comprehensive either of the thresholds or limits of sensitivity shows that striking irregularity and not uniformity characterizes the distribution of chromatic sensitivity in the peripheral retina. This is in direct opposition, it will be remembered, to the

claim made by Hess (6) that constancy of ratio of sensitivity to the paired colors prevails throughout the retina which claim, it will be remembered, was advanced by Hering (7) in support of his own theory and in refutation of Fick's (8) and Leber's (9) modifications of the Helmholtz theory to explain the color blindness of the peripheral retina. So far as we are able to determine no one intensity or set of conditions will give coincidence of limits in all meridians for any two colors inside the limits of white light vision.

In conclusion it may not be out of place to point out the bearing of these results on the work of the clinic. In the practice of perimetry as applied to diagnosis it is commonly accepted that the field of vision for the normal eye may be divided concentrically from periphery to center in the following order: white light and form, blue, red and green. It is obvious from the fore-going results (*a*) with stimuli taken from the prismatic and equal energy spectra and (*b*) from the effects obtained by varying the intensity of the stimuli that the responsibility for such a rating of the color fields rests for the greater part with the relative intensities of the pigment stimuli used in the work of the clinic. That is, the limits of sensitivity to red, yellow, blue and white light for stimuli of high intensities are coincident; for stimuli of lower intensities taken from the prismatic spectrum they are rather widely concentric; and for stimuli of equal energies of the order of intensity of 27.563×10^{-10} watt they are interlacing.

Another feature of interest is the claim that has been made by certain clinicians, but not generally accepted, we believe, that the interlacing of the limits for blue and red indicates a pathological disturbance in the relative distribution of sensitivities. While we are not disposed to dispute this conclusion because of a too meager knowledge of all of the data that should be taken into consideration in its evaluation, still we do think it fair to note that pathological disturbances are only one set of factors that may contribute to such a result and that widely different results may be gotten with the same eye with no greater differences in the test conditions than may occur from time to time in the same

clinic or laboratory unless a clear understanding is had of the factors which affect the apparent powers of response of the peripheral retina and adequate means are exercised for their control. These factors are, so far as we are able to list them, composition, area, intensity of the stimulus and duration of the stimulation, breadth of pupil, the intensity of the general illumination and the state of adaptation of the retina, and the brightness of the preëxposure and surrounding field. Obviously if the determination of the apparent limits is to be given clinical significance the work should be done under conditions of work which have been most carefully standardized, for the apparent limits are a resultant of these conditions as well as of the actual distribution of sensitivities.

The degree of importance that is attributed by at least one clinician to the absolute and relative distribution of sensitivities over the retina may be indicated by the following quotation from a recent work on perimetry. "Contraction of the form fields shows the degree of disease of the visual tract. It is better evidence of the real condition of the visual path than an ophthalmoscopic study can possibly furnish. The evidence is minute and analytical. The color fields and color changes moreover furnish a more delicate test in the early stages of the disease and at times furnish a clue to the seat of the trouble before an appreciable change has taken place in the form field" (**10**).

Summary of Results and Conclusions

The more significant features of the above results may be summarized briefly as follows:

1. The far periphery of the retina is not blind to red, blue and yellow. It is merely deficient in sensitivity to these colors. That is, with stimuli of sufficient intensity the limits of red, blue and yellow coincide with the limits of white light vision. The blindness to green, however, is for our observers absolute.

2. The amount of change of intensity required to produce a detectable change in the apparent limits of sensitivity in the more remote parts of the retina is very great. This

amount changes very irregularly from center to periphery of the retina in a given meridian and from meridian to meridian as might be expected from the great irregularity in the distribution of sensitivity in the peripheral retina. (Cf. 'Chromatic Thresholds of Sensitivity from Center to Periphery of the Retina and their Bearing on Color Theory,' Psychol. Rev., 1919, **26**, pp. 16–42.)

3. Two other important phenomena may also be mentioned as a result of this irregularity. (*a*) The shape of the zone of sensitivity to a given color changes with the intensity of the stimulus employed in making the determination. And (*b*) when stimuli of equal or of the same order of intensity are used the limits for red, yellow and blue are found to interlace or crisscross each other irregularly rather than to coincide in complementary pairs as was reported by Hegg, Hess and Baird in a more limited investigation of the retina's powers of response. The former phenomenon is the direct corollary of the difference in the rate of decrease of sensitivity to a given color in passing from the center to the periphery of the retina in the different meridians; the latter, to the change in the ratio of sensitivity to the different colors from meridian to meridian. The lack of uniformity of grading of function from point to point in the periphery of the retina, reported in this and previous papers, while striking, can scarcely be considered as surprising. It is in fact just what might be expected of those parts of a sense organ which are little used and poorly developed.

4. The responsibility of the accepted clinic rating of limits in the order from widest to narrowest of blue, red and green doubtless for the greater part rests with the relative intensities of the pigment stimuli used in the work of the clinic. With stimuli of high intensity the limits for red, yellow and blue coincide with the limits of white light vision; for stimuli of lower intensities, taken from the prismatic spectrum, they are rather widely concentric; and for stimuli of equal energies of medium intensities they are interlacing.

5. The interlacing of limits for red and blue is a normal result for stimuli of equal energy of medium intensities. It

may not therefore be due to pathological disturbances in the distribution of sensitivities as has been claimed by certain clinicians. In all responsible work on the determination of the apparent limits it is obviously of great importance to bear in mind that the results are dependent both upon the actual distribution of sensitivity and the numerous factors which affect the apparent powers of response of the peripheral retina.

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THE LIMITS OF COLOR SENSITIVITY: EFFECT OF BRIGHTNESS OF PREËXPOSURE AND SURROUNDING FIELD

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Introduction

The difficulty of getting reproducible results in determinations of the color sensitivity of the peripheral retina is a common complaint among clinic workers. This difficulty is so great as to lead many seriously to question the value of such determinations in the work of diagnosis. Their value in diagnosing and in checking up the course of some of the most serious affections of the eye is readily conceded, however, provided the needed precision can be attained. The need of greater precision of working in the laboratory, while less important to human welfare, is no less insistent. These combined needs led us several years ago to make a study of the variable factors which influence the chromatic response, the details of which are still in progress. Some of these factors pertain to the control of the stimulus, some are peculiar to the response of the eye itself. All may be standardized and controlled. The normal eye is highly sensitive and complex in its responses but not inherently erratic. While the abnormal eye may be more erratic, one of the symptoms it may be of its abnormality, there should be so far as we can see no essential difference in the technique of the study and of the testing of its functioning. In fact a characteristic difference in this regard, which can be determined with certainty only when other variable factors are controlled, may well be found to serve as a clue to an early diagnosis of its abnormality.

The variable factors which influence the chromatic response of the retina are, so far as we have discovered, the wave-length and the purity of the stimulus, the intensity of

the stimulus and the visual angle, length of exposure of the eye, accuracy and steadiness of fixation, general illumination and state of adaptation of the retina, breadth of pupil, and the brightness of the preëxposure and of the field surrounding the stimulus. We have already published considerable data on the effect of these factors in earlier papers (**1**). It will be the special purpose of the present paper to deal with the last two, the brightness of the preëxposure and of the surrounding field. A detailed explanation of the effect of these two factors on the amount of the chromatic response has been given in the second of the papers referred to above (**1**). A brief explanation and statement of principles will suffice here.

1. When a small colored stimulus, surrounded by a field, for example, of white or black is viewed, a sensation is given which consists of the color mixed with black or white, due to a contrast sensation induced from the surrounding field. The effect of fusing a color with white or black is twofold. (*a*) There is a quantitative effect due to the inhibition of the chromatic excitation by the achromatic. In general, in the central retina at medium and high illuminations, white inhibits color the most, the grays in order from light to dark next, and black the least. Also the amount of the inhibitive action varies with the different colors, with the part of the retina at which the stimulation takes place, and the state of brightness adaptation of the retina. The amount of induction depends upon the difference in brightness between the stimulus and the surrounding field; it increases with the distance from the fovea and with decrease in the general illumination; and, with a given difference in brightness between the stimulus and the surrounding field, it is greater with a white than with a black field—also the amount of increase of induction with decrease of illumination and with increase of distance from the fovea is greater with a white than with a black field. And (*b*) there is also a qualitative effect. The hue of certain colors is changed by the action of the achromatic excitation. The change is greatest when the stimuli are blue and yellow. For example, yellow when

mixed with black gives a greenish yellow which with the right proportion of components may become an olive green; and blue when mixed with white or light gray gives a sensation of reddish blue.

2. When making the color observation in the peripheral retina, the observer is given a short period of preparation before the stimulus is exposed, in which to obtain and hold a steady and accurate fixation. This introduces the factor of preëxposure for, during this period of preparation, the area which is to be stimulated by color receives a previous stimulation. This previous stimulation, when it differs in brightness from the color, gives a brightness after-image which mixes with the color sensation and both reduces its saturation and modifies its color tone. If the preëxposure is lighter than the stimulus color, it adds by after-image a certain amount of black to the succeeding color impression; if darker, it adds a certain amount of white. Since both white and black as after effect reduce the sensitivity to color, the eye is rendered more sensitive when no after-image is given, that is when the preëxposure is of the same brightness as the color. The preëxposure should, therefore, be a gray of the brightness of the color. No brightness after-image will then be added to the succeeding color impression to modify either its saturation or color tone. The only brightness change acting upon it will be due to the slight adaptation to this gray during the short time of preëxposure. Even closing the eye, as is frequently done before stimulating, is equivalent to giving a black preëxposure.

The general principle then is clear. There remains only to explain why in the peripheral retina the short preëxposure which takes place while the eye is obtaining a steady fixation has so much effect on the color stimulation immediately following. Two reasons are found for this. (*a*) The after-image reaction of the peripheral retina is extremely quick. While some slight variation is found at different angles of excentricity, in general the peripheral after-image seems to reach its maximal intensity with a few seconds of stimulation. This amount of time is usually consumed in obtaining fixa-

tion and preparing for the stimulation, hence in each observation there is fused with the color sensation about as strong a brightness after-image as can be aroused. For this reason alone it is readily seen why the brightness of the preëxposure is of so much greater consequence in the peripheral than in the central retina, where the maximal intensity of after-image is, roughly speaking, obtained from a stimulation of 40–60 seconds or longer. (*b*) There is apparently no latent period in case of the peripheral after-image. It flashes out at full intensity immediately upon the cessation of the stimulation. Thus there is no possibility of escaping the full effect of the brightness after-image on the stimulus color as might happen in the central retina where the latent period obtains, if there were a very short exposure to stimulus color.

Conditions under which the Work was Done

The determinations were made in an optics room of the type described in previous articles (2). The illumination was kept constant at a value at the point of work of 42 foot-candles, vertical component; 31.2 foot-candles, 45 degree component; and 12.5 foot-candles, horizontal component. Three investigations were conducted.

1. A determination was made of the effect on the apparent limits of color sensitivity of variations in the brightness of the field surrounding the stimulus. Three fields were used: the standard white of the Hering series, giving a surface brightness at the intensity of illumination used of 0.0209 candle-power per sq. in.; the standard black of the series, giving a surface brightness of 0.00094 candle-power per sq. in. and grays of the brightness of the color at the limits of sensitivity in each of the meridians investigated. These grays ranged in brightness in the different meridians from 0.00350 to 0.00395 cp. per sq. in. for red; 0.01445 to 0.0189 for yellow; 0.01058 to 0.01185 for green; and 0.00289 to 0.00366 for blue. In order to study the effect of brightness of surrounding field in separation, the preëxposure was in each case made of the brightness of the color at the point of investigation.

2. A determination was made of the effect on the apparent limits of sensitivity of varying the brightness of the preëxposure. Again three brightnesses were used: the standard Hering white; the standard Hering black; and grays of the brightness of the color at the limits of sensitivity in each of the meridians investigated. The photometric value of the white, black and the range of grays for each of the colors are given in 1 above. In this series of experiments the surrounding field was made in each case of the same brightness as the color at the point of investigation.

3. A determination was made of the combined effect of preëxposure and surrounding field on the apparent limits of sensitivity. The same three brightnesses were used as in the preceding investigations. In these cases, however, the surrounding field and preëxposure were both made of the same brightness, *i.e.*, both white, black or grays of the brightness of the color at the limits of sensitivity in the meridians investigated.

Since the results obtained were meant only to be comparative of the effect of varying given factors, it was deemed sufficient to make the determinations with pigment stimuli. So obtained the results are moreover more nearly what may be expected in the work of the clinic. The standard red, yellow, green and blue of the Hering series of papers were used. The work was done with the rotary campimeter described in previous papers (**3**). With the control of surrounding field afforded by the campimeter, this apparatus combines the rotary features of the perimeter. Without some apparatus combining both of these features we have not found it possible to make a determination of the apparent limits of sensitivity with an adequate control of the brightness of the surrounding field and of the preëxposure. The need of an apparatus in the clinic by means of which this control may be accomplished is obvious. Not only is it impossible to secure an adequate control of these two important factors by means of the standard perimeter, but a very great practical difficulty is encountered in daylight work in getting an equal illumination of the pigment stimulus at

different points in the field of vision and a constant illumination from sitting to sitting. In case of artificial illumination the latter difficulty can perhaps be eliminated with care; but the task of securing an equal effective illumination of the stimulus from point to point in the same meridian and of corresponding points in different meridians is practically impossible in case of any perimeter now in use, because of the unequal shading of the moving stimulus by the observer, the varying inequalities of the incident and reflecting angles, etc. In case of the instrument used by us these difficulties are minimized by using a stationary pigment surface, 20 x 20 cm. placed with special reference to evenness of illumination at some constant distance (in the present work 45 cm.) behind the stimulus opening in the campimeter and by securing the excentric stimulation by shifting the fixation from point to point along an arm specially constructed for the purpose. For other points of criticism of the perimeter as an instrument of precision for either light or dark room work the reader is referred to former papers. The preëxposure was secured by inserting the appropriate pigment surface between the stimulus card and the stimulus opening in the campimeter. The duration of the preëxposure was kept constant at 2 seconds. The stimulus opening in the campimeter was 15 mm. in diameter. At the eye, 25 cm. distant, this subtended a visual angle of 3° 26′.

The more important results given in this paper have been confirmed repeatedly both in the graduate and undergraduate work in our laboratory. The determination of the effect of the brightness of preëxposure and surrounding field on the apparent limits of color sensitivity has in fact formed a part of the drill work in the undergraduate laboratory for several years. Space will be taken here for the results of only one observer—the observer whose results have been given in the preceding studies on the color sensitivity of the peripheral retina.

As has already been indicated, the effect of brightness of the preëxposure and of the surrounding field falls under the general heading of the inhibitive action of the achromatic

excitation on the chromatic. This action takes place however the achromatic excitation is aroused—by the admixture of white light, by after-image, by contrast, etc. It may be strikingly and conveniently demonstrated to large numbers at once in the following lecture room experiments. (*a*) Set up side by side on three color mixers discs made up of 180 degrees of color, *e.g.* blue, and 180 degrees of white, 180 degrees of blue and 180 degrees of gray of the brightness of the blue, and 180 degrees of blue and 180 degrees of black. When mixed, although the eye receives the same amount of colored light from each set of discs, the mixture with black seems to have lost but very little, if any, color; the mixture with white is a lavendar with but little color; and the mixture with gray of the brightness of the color, in this case a very dark gray, is less saturated than the mixture with black. When different grays are used the saturation decreases apparently in graded steps as white is approached. The demonstration can be made on a single color mixer by compounding the color disc with white, black and gray discs of different breadths or radii. When rotated this gives the effect of a surface made up of three concentric zones or rings, one in which the color is mixed with white, one with gray and the other with black. The demonstration may be made roughly quantitative by determining the proportions of color required to give the chromatic threshold in black, white and the grays; also by determining the proportions of color and the achromatic series to give equal saturations.

(*b*) Prepare a preëxposure surface, half white and half black, 50 x 60 cm. Expose the eye 15–20 seconds and project the after-image on a colored surface, *e.g.*, blue, of the same dimensions. The half of the field preëxposed to black will appear a very pale unsaturated lavendar, while the half preëxposed to white will be a dark strongly saturated blue, although the eye receives the same amount of light from both halves of the field. As the after-image dies away the two halves of the field become more and more nearly alike in saturation and color tone. If desired, the preëxposure surface may be made of white, black and a series of graded

grays, appropriately arranged. When this is done the graded loss in saturation due to the different brightnesses of the after-image may be observed. This demonstration also may be made quantitative by finding the threshold of color after the eye has been preëxposed for 15–20 seconds to white, black and the grays.

(*c*) Prepare contrast discs with narrow rings of color and inside and outside surfaces of black, white and a gray of the brightness of the color, respectively. Set up on color mixers side by side and rotate to smooth out all margins. The colors are lightened and darkened respectively by contrast induced by the black and white fields. The effect of these achromatic excitations on the hue and saturations of the colors is similar to that obtained in the former experiments. A more striking effect is produced if a mixed color, *e.g.*, orange, is used. The quantitative features noted above can also be utilized in this demonstration by employing for the contrast ring in each case a gray of the brightness of the color and enough of the color to give the threshold of color sensation when acted upon by the white and black inductions. The effect of induction and after-image, it will be remembered, are not nearly so striking in the central as in the peripheral retina. Much more induction with a given brightness difference between the inducing and the contrast field, for example, is produced in the peripheral retina, and only a short period of preëxposure (2–3 seconds) is required to give a strong after-image with no latent period.

Results

The following results were obtained: (1) The widest angular limits of the color zones were obtained when the preëxposure and surrounding field were of the same brightness as the color. (2) When the brightness of preëxposure and surrounding field were different from that of the color, the effect of surrounding field was less than that of preëxposure; and the effect of either is always less than the combined effect of both. (3) In some meridians the effect of surrounding field alone narrowed the limits as much as

11 degrees; the effect of preëxposure alone, as much as 17 degrees; and the combined effect of preëxposure and surrounding field, as much as 20 degrees.

(4) The amounts the limits were narrowed for red, yellow, green and blue, respectively, by a white preëxposure alone ranged in the different meridians[1] from 4–15 degrees, 2–17 degrees, 3–15 degrees, and 4–12 degrees; by a black preëxposure from 3–11 degrees, 3–10 degrees, 4–13 degrees, and 2–12 degrees; by a white surrounding field 1.5–10 degrees, 2–9 degrees, 2–11 degrees, and 2–10 degrees; by a black surrounding field 1–8 degrees, 1–8 degrees, 2–10 degrees, and 1.5–9 degrees; by a combined white preëxposure and white surrounding field 5–19 degrees, 2–20 degrees, 4–20 degrees, and 5–17 degrees; by a combined black preëxposure and black surrounding field 4–17 degrees, 5–12 degrees, 7–18 degrees and 5–18 degrees. When the effect of a white or black surrounding field alone was wanted, the preëxposure was made of the same brightness as the color at the point of investigation; similarly when the effect of a white or black preëxposure was wanted, the surrounding field was made of the same brightness as the color at the point of investigation. The value of the limits with a preëxposure and surrounding field of the same brightness as the color served in each case as the standard value in terms of which to estimate the amounts the limits were narrowed by the white and black preëxposures and surrounding fields and their combinations.

These values, it will be remembered were obtained with a very precise control of the illumination of the working surfaces. It is obvious that a much greater variability of result should be expected had there been no better control of the constancy of illumination than is ordinarily exercised in office and clinic work, and too often in laboratory work. The effect on both the limits and hue of the color of such variations in the daylight illumination of the working surfaces as are apt to occur over long periods of time when no especial control is exercised, will be given in a later paper.

[1] In the order shown in the tables.

In order to realize how profoundly the powers of chromatic response must have been affected to change the limits of sensitivity by the amounts represented by the above figures one must bear in mind how abruptly sensitivity falls off in the far periphery of the retina. A determination of the thresholds of color in the temporal meridian with preëxposure

Table I

Limits of Color Field for Red

Showing the Effect of Brightness of Preëxposure, Brightness of Surrounding Field, and the Combined Effect of Brightness of Preëxposure and Surrounding Field on the Apparent Limits for Red

Meridian	Effect of Preëxposure[1]			Effect of Surrounding Field[2]			Combined Effect of Preëxposure and Surrounding Field		
	Gray of Brightness of Color	White	Black	Gray of Brightness of Color	White	Black	Gray of Brightness of Color	White	Black
Upper 0°......	58	45	47	58	48	50	58	40	41
Nasal 25°......	49	43	43	49	46	46	49	41	39
" 45°......	49	43	41	49	46	44	49	38.5	37.5
" 70°......	47	43	42.5	47	45.5	44.5	47	41	40
" 90°......	43	38	37	43	41.5	40	43	38	38
" 110°......	47	42	42	47	43	43	47	41	42.5
" 135°......	50	46	45	50	48	47	50	45	44
" 155°......	51	47	47	51	48.5	48.5	51	46	46
Lower 180°......	60	53	56	60	55	57	60	52	56
Temporal 25° ..	73	59	68	73	66	70	73	55	62
" 45° ..	79	64	74	79	70	76	79	60	72
" 70° ..	85	75	80	85	80	82	85	69	78
" 90° ..	89	83	85	89	85	88	89	80	84
" 110° ..	89	82	85	89	84	86	89	80	83
" 135° ..	85	78	82	85	81	83	85	77	81
" 155° ..	75	62	65	75	65	68	75	60	64

and surrounding field of the same brightness as the color for red, yellow, green and blue at 5 degrees, 3 degrees, 2 degrees and 1 degree respectively from the limit shows the following values: for red, 132, 150, 250 and 320 degrees; for yellow, 100, 150, 240 and 330 degrees; for green 130, 145, 260 and 345 degrees; and for blue 130, 145, 200 and 310 degrees.

[1] In determining the effect of the different brightnesses of preëxposure, the brightness of the surrounding field was made equal to that of the color at the point of investigation.

[2] In determining the effect of the different brightnesses of surrounding field, the brightness of the preëxposure was made equal to that of the color at the point of investigation.

For red thus there was an increase of 172.7 per cent. in the threshold in passing to the limit from a point 5 degrees from the limit; for yellow an increase of 260 per cent.; for green an increase of 207.7 per cent.; and for blue an increase of 207.7 per cent. For a more detailed experimental analysis of the effect of preëxposure, surrounding field, intensity of

Table II

Limits of Color Field for Yellow

Showing the Effect of Brightness of Preëxposure, Brightness of Surrounding Field, and the Combined Effect of Brightness of Preëxposure and Surrounding Field on the Apparent Limits for Yellow.

Meridian	Effect of Preëxposure[1]			Effect of Surrounding Field[2]			Combined Effect of Preëxposure and Surrounding Field		
	Gray of Brightness of Color	White	Black	Gray of Brightness of Color	White	Black	Gray of Brightness of Color	White	Black
Upper 0°	47	41	37.5	47	41	39	47	38	36
Nasal 25°	42	39	38	42	40	39	42	38.5	37
" 45°	42	37	36	42	40	38	42	37	35.5
" 70°	46	42	40	46	44	42	46	42	39
" 90°	44	42	40	44	42	41	44	42	38.5
" 110°	46	42	38	46	43	41	46	41	37
" 135°	50	46	45	50	48	47.5	50	46	45
" 155°	48	44	44	48	46	46	48	43	43
Lower 180°	59	51	54	59	53	56	59	47	52
Temporal 25°	65	48	55	65	58	61	65	45	53
" 45°	73	63	70	73	68	72	73	62	67
" 70°	87	70	84	87	79	86	87	69	80
" 90°	89	75	85	89	80	87	89	72	84
" 110°	89	81	86	89	83	87	89	80	85
" 135°	87	80	84	87	82	85.5	87	78	84
" 155°	72	60	65	72	63	67	72	59	63

the illumination of the visual field, amounts of induction with different brightness relations of surrounding field to stimulus at different intensities of illumination, etc., and the effect of all of these on the thresholds of color and the limits of sensitivity the reader is referred to the first two papers cited in the appended bibliography (**1**).

5. In those meridians in which the limits are wide there is a general tendency for the white preëxposure and surrounding field to narrow the limits more than a black preëxposure

[1] Brightness of Surrounding Field: gray of the brightness of yellow.

[2] Brightness of Preëxposure: gray of the brightness of yellow.

and a black surrounding field. We have stated in our introduction that the amount of inhibition of the chromatic by the achromatic excitation varies with the color, the part of the retina stimulated and the state of adaptation of the retina. This statement applies also to the relative effects of white and black. In the central retina at medium and high illuminations white inhibits color much more than black.

Table III

Limits of Color Field for Green

Showing the Effect of Brightness of Preëxposure, Brightness of Surrounding Field, and the Combined Effect of Brightness of Preëxposure and Surrounding Field on the Apparent Limits for Green

Meridian	Effect of Preëxposure[1]			Effect of Surrounding Field[2]			Combined Effect of Preëxposure and Surrounding Field		
	Gray of Brightness of Color	White	lack	Gray of Brightness of Color	White	Black	Gray of Brightness of Color	White	Black
Upper 0°......	36	26	29	36	28	31	36	27	22
Nasal 25°......	35	30	27	35	31	29	35	26	21
" 45°......	38	30	28	38	32	30	38	29	24
" 70°......	39	34	31	39	36	31	39	32	27
" 90°......	39	35	33	39	37	35	39	33	28
" 110°......	37	31	31	37	33	33	37	31	30
" 135°......	37	32	29	37	34	31	37	31	25
" 155°......	33	30	29	33	31	30	33	29	26
Lower 180°......	37	32	31	37	34	33	37	28	26
Temporal: 25° ..	37	30	30	37	34	35	37	28	26
" 45° ..	42	34	36	42	39	40	42	30	33
" 70° ..	61	51	53	61	56	57	61	47	50
" 90° ..	69	56	60	69	60	62	69	50	53
" 110° ..	65	53	56	65	58	61	65	46	50
" 135° ..	57	42	44	57	46	47	57	37	39
" 155° ..	44	39	37	44	41	39	44	35	34

At these illuminations therefore a black preëxposure and surrounding field are much more unfavorable than white. At lower illuminations this difference in effect becomes less pronounced. In the far periphery of the retina the following are some of the conditions which contribute to make black as preëxposure and surrounding field give wider limits of sensitivity. (*a*) A condition of low illumination and a state of low illumination adaptation. (*b*) A darkening of all of the

[1] Brightness of Surrounding Field: gray of the brightness of green.

[2] Brightness of Preëxposure: gray of the brightness of green.

colors, particularly red and yellow (the Purkinje shift of the peripheral retina). This brings the brightness of the color nearer to black than to white and the stronger relative darkening of red and yellow than of their neutral or colorless preëxposures and surrounding fields, increases the contrast

Table IV

Limits of Color Field for Blue

Showing the Effect of Brightness of Preëxposure, Brightness of Surrounding Field, and the Combined Effect of Brightness of Preëxposure and Surrounding Field on the Apparent Limits for Blue

Meridian	Effect of Preëxposure[1]			Effect of Surrounding Field[2]			Combined Effect of Preëxposure and Surrounding Field		
	Gray of Brightness of Color	White	Black	Gray of Brightness of Color	White	Black	Gray of Brightness of Color	White	Black
Upper 0°......	52	40	46	52	42	48	52	35	34
Nasal 25°......	45	39	39	45	41	42	45	38	36.5
" 45°......	48	44	46	48	45	46	48	40	40
" 70°......	46	41	41	46	44	44	46	41	41
" 90°......	52	42	42	52	48	47	52	42	40
" 110°......	50	46	45	50	47.5	47	50	44	43
" 135°......	52	47.5	47.5	52	50	49	52	46	46
" 155°......	58	48	46	58	51	49	58	43	42
Lower 180°......	70	63.5	62	70	66	64.5	70	61	59
Temporal: 25° ..	70	62	65	70	65	68.5	70	56	59
" 45° ..	79	71	73	79	73	75	79	65	69
" 70° ..	86	78	82	86	80	84	86	77	80
" 90° ..	91	86	85	91	89	89	91	84	84
" 110° ..	91	85	85	91	88	88	91	83	83
" 135° ..	89	84	83	89	86	85	89	83	83
" 155° ..	80	75	75	80	77	77	80	75	74

and after-image effect for white and decreases it for black. The darkening of red and yellow in passing to the far periphery of the retina is very great. In the nasal half of the retina with its wide limits, the effect of this darkening on the results of our determinations was, of course, the most pronounced. As colors darken, there is, when a certain point in the process is reached, varying with the color, a tendency for them to lose their saturation very rapidly. (*c*) Achromatic induction increases very strongly with decrease of illumination and therefore increases in passing from the center to the periphery

[1] Brightness of Surrounding Field: gray of the brightness of blue.

[2] Brightness of Preëxposure: gray of the brightness of blue.

of the retina. It increases much faster for white than for black.

In the meridians in which the limits are narrower the situation is more nearly as it is in the central retina. Here the tendency is for the limits to be narrowed more by a black

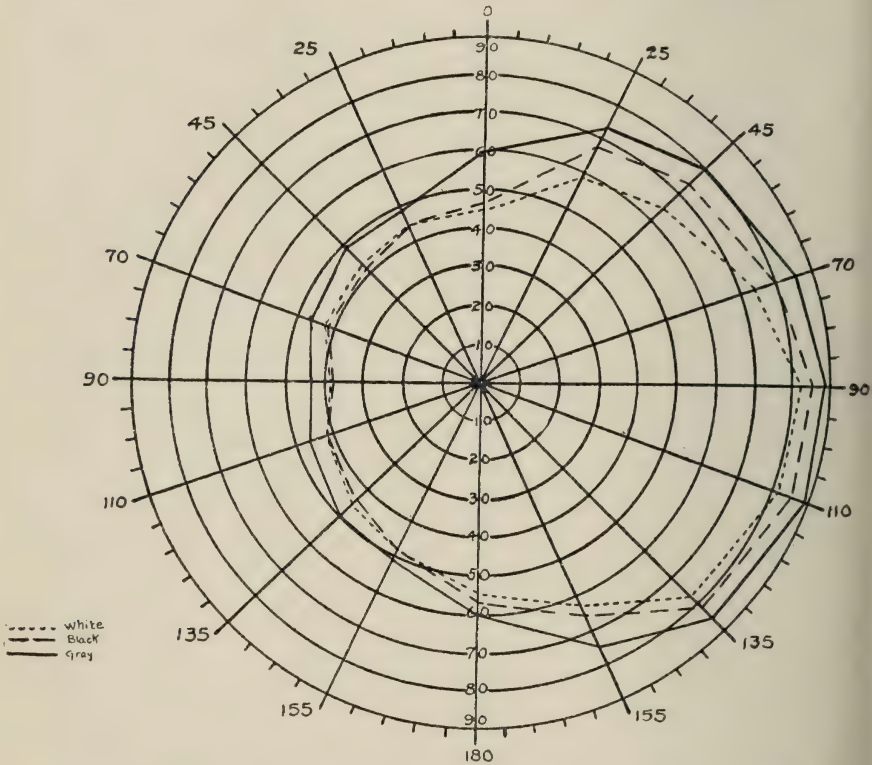

FIG. I. Effect of brightness of preëxposure on the limits of the color field. In this chart are shown the apparent limits for red with preëxposures respectively of white, black, and gray of the brightness of the color at the point of investigation, surrounding field in each case gray of the brightness of the color at the point of investigation.

than by a white preëxposure and surrounding field. In some meridians the amount of narrowing is approximately equal for both. Another factor which tends to make the effect more nearly the same in these meridians for all backgrounds and preëxposures is the more abrupt falling off in sensitivity. That is, more effect on sensitivity is required here to change the limits by a detectable amount than is

required in those portions of the retina where the sensitivity grades off more slowly.

A detailed representation of the results is given in Tables I–IV. and a graphic representation of a part of the results in Figures 1–6. In the tables results are given separately

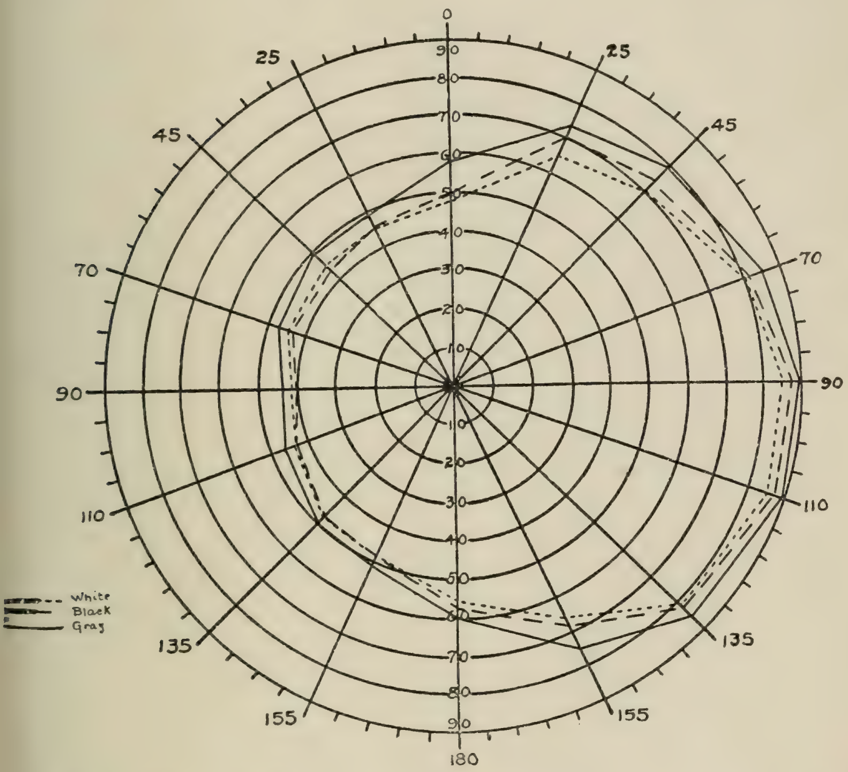

FIG. 2. Effect of brightness of surrounding field on the limits of the color field. In this chart are shown the apparent limits for red with a surrounding field respectively of white, black, and gray of the brightness of the color at the point of investigation, preëxposure in each case gray of the brightness of the color at the point of investigation.

for the effect of preëxposure, surrounding field and combined effect of preëxposure and surrounding field for each of the four colors: red, yellow, green and blue. In case of the figures, however, space has been taken to represent separately the effect of preëxposure and surrounding field for only one of the colors, red—Figs. 1–3. Figs. 3–6 show

the combined effect of preëxposure and surrounding field on each of the four colors. In our previous papers the representation of results has been in terms of position on the retina. In this paper the representation has been made in terms of field of vision.

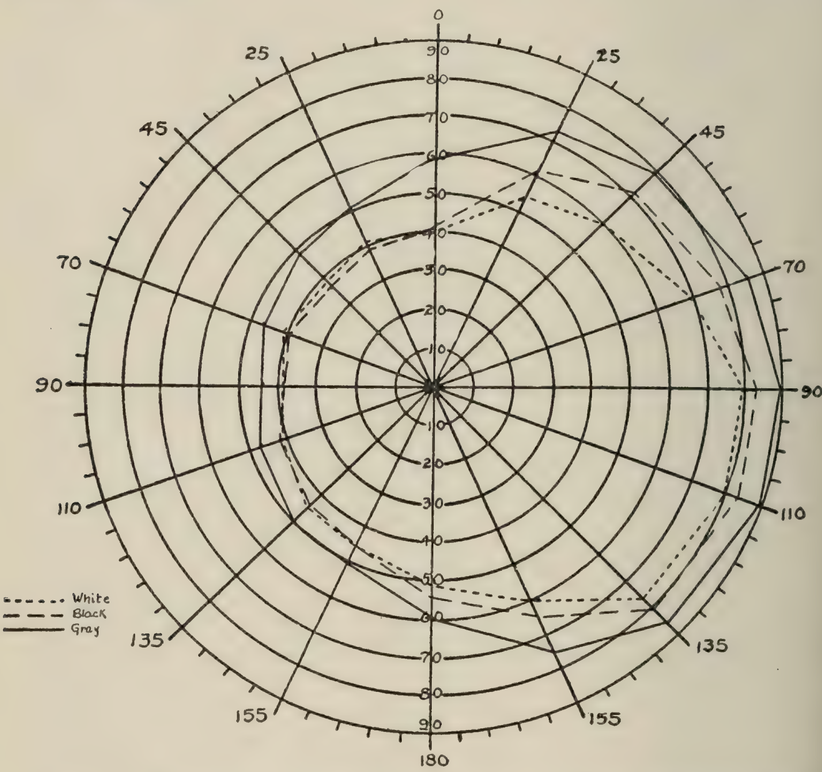

FIG. 3. The combined effect of brightness of preëxposure and surrounding field on the limits of the color field. In this chart are shown the apparent limits for red with both preëxposure and surrounding field respectively of white, black, and gray of the brightness of the color at the point of investigation.

Conclusion

It is quite obvious from the preceding data that reproducible results can not be hoped for in perimetric or campimetric determinations of the sensitivity of the peripheral retina unless the variable effects of preëxposure and surrounding field be eliminated from the conditions of work. This can be done completely only by making the brightness of

the preëxposure and surrounding field in each case the same as that of the color employed and working under constant intensity of illumination. Among the effects of a variable intensity of illumination on the results of a perimetric or campimetric determination the following two may be men-

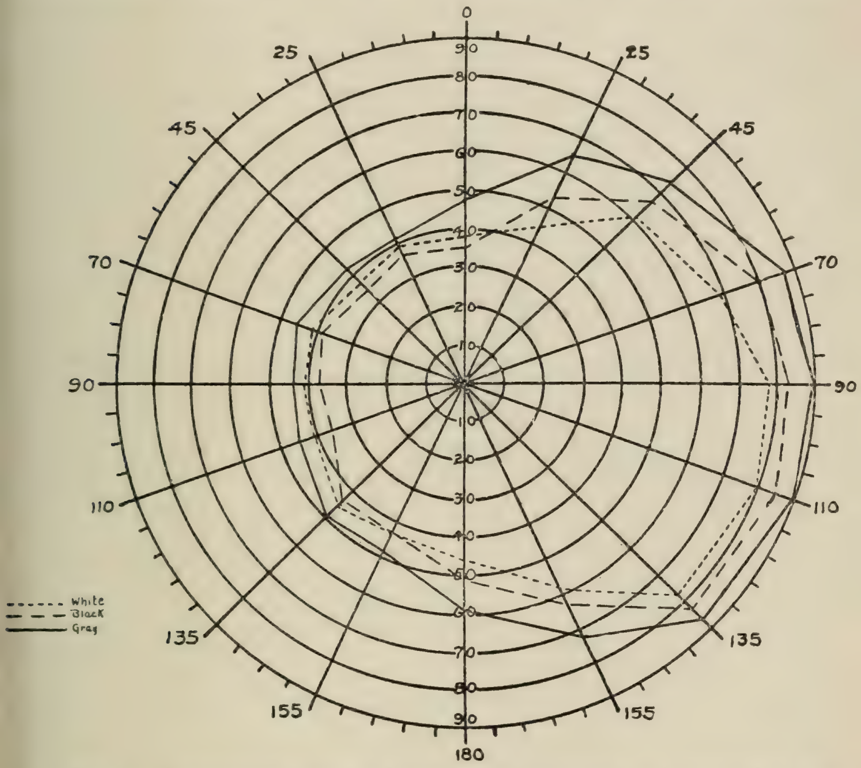

FIG. 4. The combined effect of brightness of preëxposure and surrounding field on the limits of the color field. In this chart are shown the apparent limits for yellow with both preëxposure and surrounding field respectively of white, black, and the gray of the brightness of the color at the point of investigation.

tioned. (*a*) When the color stimulation is given by light reflected from pigment stimuli of a given coefficient of reflection the amount of colored light obtained depends upon the intensity of light incident on the reflecting surface. And (*b*) a brightness match of preëxposure and surrounding field with the stimulus surface will not hold at different illuminations (the Purkinje phenomenon).

We have worked out in previous papers the conditions under which the desired standardization of intensity and color value of illumination and control of brightness of preexposure and surrounding field may be obtained in labor-

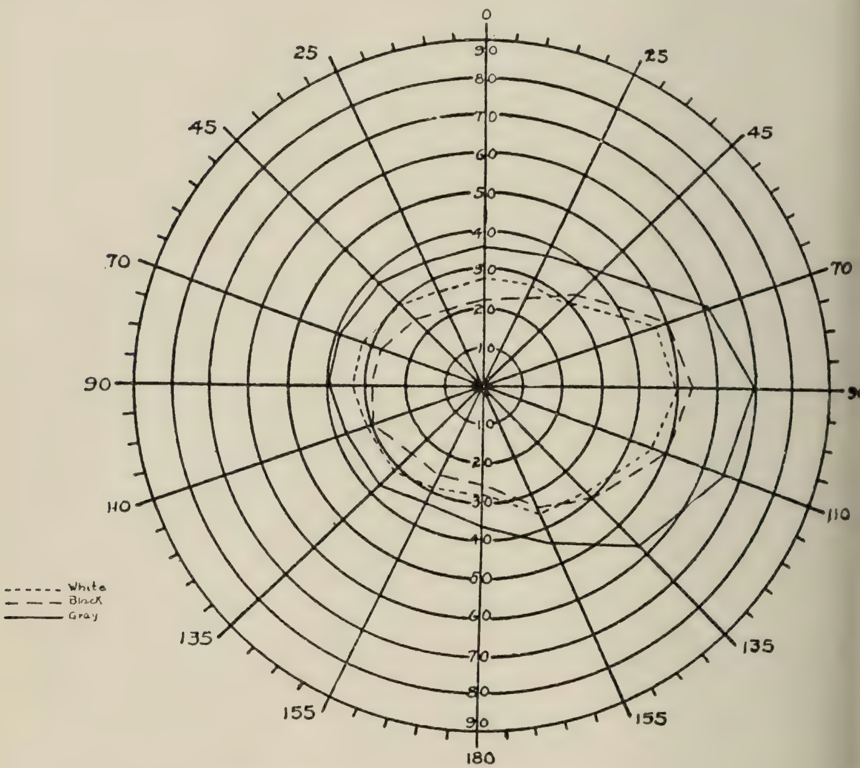

Fig. 5. The combined effect of brightness of preëxposure and surrounding field on the limits of the color field. In this chart are shown the apparent limits for green with both preëxposure and surrounding field respectively of white, black, and gray of the brightness of the color at the point of investigation.

atory campimetry (**4**). These conditions however are scarcely feasible for the work of the office or clinic. We have therefore more recently devised and constructed a perimeter by means of which equal illumination of the stimulus is received at every point on the perimeter arm in all meridians and the effect of brightness of preëxposure and surrounding field can be eliminated with an ease and speed of manipulation which

should be feasible for office and clinic work and with a completeness of result that should be adequate for this type of work. We have in fact constructed two types of perimeter either one of which provides for the uniform illumination of the arm of the perimeter. The perimeters will be described in a later paper.

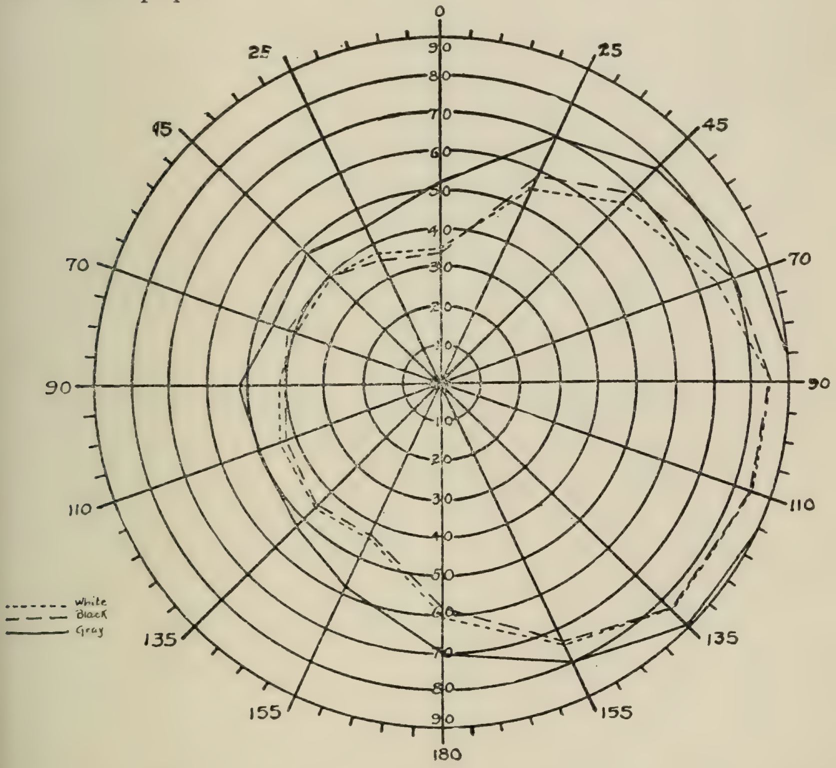

FIG 6. The combined effect of brightness of preëxposure and surrounding field on the limits of the color field. In this chart are shown the apparent limits for blue with both preëxposure and surrounding field respectively of white, black, and gray of the brightness of the color at the point of investigation.

COMMENT

A much more detailed study of the quantitative relations of the chromatic and achromatic components of the visual sensation for different intensities of stimulus and for different states of the reacting eye is needed. There are many important practical bearings of the knowledge that would be

gained by such a study. For example, it is often deemed sufficient to give a colorimetric specification of a light at one intensity alone in spite of the fact that the saturation, even the hue of the color, changes with the intensity as well as the composition of the light. We are all familiar in a general way with the fact that even the sensation aroused by a spectrum band of light begins as achromatic or colorless at very low intensities, passes through saturation and hue changes with increase of intensity of light and finally becomes colorless again at high intensities. We have pointed out many times in connection with problems of lighting (5) that while a specification of the composition of light is independent of intensity, a true colorimetric specification may not, depending on the method used, be definite unless it is accompanied also with a specification of intensity. Filters designed to give a certain coloration of light can not be depended upon to give this subjective coloration at all intensities even though the wave-lengths transmitted are in the same proportions. Indeed when used in connection with the same intensity of source the coloration of the illumination of an object as seen by the eye, particularly the saturation, will vary at different distances from the source. The lack of realization of this dependence of the color of light on its intensity as well as its composition has doubtless played no small part in the popular confusion which exists as to the comparative color values of different artificial lights and of the closeness of approximation of certain artificial lights to daylight. The surface of a Welsbach mantle, 0.7 per cent. ceria, viewed directly is, for example, whitish; but the reading page illuminated by it to ordinary working brightness appears distinctly yellowish green. Again the illumination given by the blue bulb lamp may be judged of different color values depending upon the intensity of light falling on the illuminated object. Complementary colors combined to gray at medium or high intensities may not be seen as colorless at low illuminations, *e.g.*, the gray produced by combining the Hering standard blue and yellow under daylight of good intensity becomes dis-

tinctly lavendarish under the same light at low intensities. Daylight itself is popularly said to become bluish at low intensities. Examples may thus be multiplied indefinitely of the apparently peculiar complexity of the selectiveness of the eye's chromatic response to intensity.

In addition to the practical bearings of the shifting of the quantitative relations of the achromatic and chromatic components in the visual sensation, with no change in the composition of light, there is the interesting problem of explanation. Many factors, it may be, are operative in the production of this phenomenon: a selectiveness of response to intensity, perhaps even a change in the range of the eye's chromatic response to wave-length with change of intensity, in case of spectrum lights; this and slight variations for change of intensity, in the cancelling proportions of the complementary colors and in the mutually inhibitive actions of the non-complementary colors, in case of mixed lights; a direct action of the achromatic excitation on the chromatic, for both simple and mixed lights; etc. It seems not only reasonable but necessary to infer this latter action because the same type of effect is produced on the color when the achromatic component of the sensation is varied in all of the following ways: by keeping the composition of the light the same and varying its intensity, by adding colorless light, by adding white or black to the sensation as after-image or contrast, and by the achromatic changes in adaptation. No other explanation seems possible when the phenomenon is produced as an effect of preëxposure and surrounding field or as we commonly say by after-image and contrast, as has been the case in the work reported in this paper.

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THE CAMPPERIMETER—AN ILLUMINATED PERIMETER WITH CAMPIMETER FEATURES.

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(By invitation.)

This apparatus was devised in response to a request from a committee appointed by this Society to work out a better standardization of the illumination of perimeters and test-charts. The request was for a feasible means of illuminating the perimeter arm with light of a good intensity and quality, so that every point on the arm in any meridian in which it might be placed would receive equal intensities of light. [ntensity and quality of illumination, however, are only two ›f the factors which influence the results of the perimetric letermination. In devising the instrument described in this ›aper it has been the purpose of the writers to provide a 'ontrol also of other factors which are of importance in the vork of the office and clinic.

The variable factors which influence the apparent limits f color sensitivity are, so far as we have been able to disover, the wave-length and purity of the stimulus, the inensity of the stimulus and the visual angle, length of exosure of the eye, the method of exposure (moving or staonary stimulus), accuracy and steadiness of fixation, the ıtensity of the general illumination of the retina and its ate of adaptation, breadth of pupil, and the brightness of ıe preëxposure and of the background or surrounding field. he most important of these, from the standpoint of the fice or clinic, are perhaps the intensity of the stimulus, the ightness of the preëxposure and surrounding field, the

intensity of the general illumination, and the accuracy anc steadiness of fixation.

(1) *Intensity of Stimulus.*—By a sufficiently wide variatior in this factor alone the fields of color sensitivity may be mad to have almost any breadth within the limits of the field o vision and to differ radically in shape. When pigment sur faces of a given coefficient of reflection are used as stimuli the illumination of the perimeter arm determines the in tensity of the stimulus light. Two methods are proposed fo securing an even illumination of the stimulus at every poin on the perimeter arn and of reproducing thi illumination from tim to time.

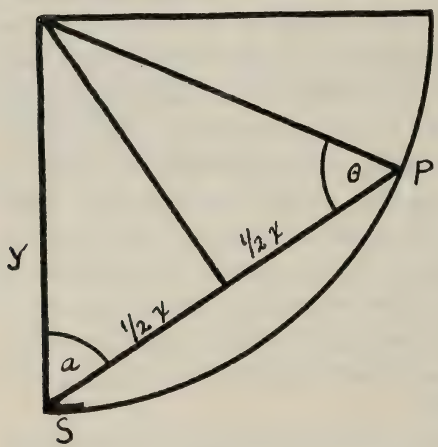

Fig. 1.

Method 1.—When th source of light is inlaid i the surface of the arn or its continuation, th illumination on this sur face will be equal fo approximately 180° o either side of the source The value of this illu mination at every poin will be equal to the nor mal flux of light from the luminous surface divided by fou times the square of the radius of curvature of the perimete arm. A perimeter embodying this principle of illumination i being constructed in the following way: A lamp-house is fast ened on the continuation of a 90° arm in such a position tha an opening in its surface facing the observer lies in the cor tinuation of the surface of the perimeter arm. This openin is filled in with diffusing glass bent to take the curvature c the arm, and shaded in such a way as to shield the eye of th physician, and the observer, without changing or interferin

with the distribution of light to the perimeter arm. The lamp-house rotates with the arm and thus illuminates it uniformly at every point in all meridians.

The principle by which an even illumination of the perimeter arm is secured by this method may be demonstrated as follows: Let S, Fig. 1, be the source of light inlaid in the surface of the arm; P, any point in the perimeter arm that is to be illuminated; x, the distance from S to P; y, the radius of curvature of the arm or the distance of the eye from the arm; a, the angle of emission of the light from the source, S; and θ, the angle of incidence of this light at the point P. Then the intensity of the light at P will be inversely as the square of the distance of P from S, or inversely as x^2, and directly as the cosine of the angle of emission a, $\frac{\frac{1}{2}x}{y}$, and the angle of incidence θ, also $\frac{\frac{1}{2}x}{y}$. That is:

$$I = I \times \frac{1}{x^2} \times \frac{\frac{1}{2}x}{y} \times \frac{\frac{1}{2}x}{y} = I\,\frac{\frac{1}{4}x^2}{x^2y^2} = \frac{I}{4\,y^2};$$

in which I is the intensity of light at P, and I the intensity at S. From this equation is derived the law of illumination of the arm, the intensity of light at any point on the arm is equal to the normal flux of light from the source, divided by four times the square of the radius of curvature of the arm.

The method has the following objections: (1) The difficulties in construction are not easy to overcome. (2) Evenness of illumination requires an approximately perfectly diffusing glass. This glass is difficult to obtain and prepare, and its transmission is apt to be low. Moreover, the light incident on the perimeter arm should approximate daylight in composition. The selective absorption required to correct the light from the lamp to this composition further reduces the intensity enormously. This double loss, first by absorption and second by the somewhat wasteful type of distribution

employed, renders it difficult to get an adequate intensit of illumination of the perimeter arm.

Method 2.—When the source of light lies in the perpen dicular to the plane of the perimeter arm at its center c curvature, it will be equidistant from every point on the arm also the angles of emission and incidence of the beam of ligh will be equal for every point on the arm. A perimeter ha been constructed embodying this principle of illumination This perimeter is shown in Fig. 2. Two arcs of the sam radius of curvature were constructed at right angles to eac other—one, a 180° arc, the perimeter arm; the other, a 90 arc, the lamp arm at the end of which is placed the source o light. In order that the source of light shall sustain a fixe relation to the perimeter arm for all positions of that arm the two arms are fastened together at the center of rotation About the source is a housing which was designed in such way as to shield the eye of the patient and the physicia without interfering with the distribution of light to th perimeter arm. This housing is made of black japanned iro and is painted a mat black on the inside, in order that, a nearly as possible, all the light which passes to the perimete arm shall radiate directly from the lamp filament. It dimensions are 4¼ by 4¼ by 5 inches. A rectangular aper ture 2⅛ inches wide was cut out of the side of the housin facing the perimeter arm, at the bottom, and for 3 inche back on the two adjacent sides. The relation of the lamp t this aperture is such that the light radiates freely withou shadows from the filament to every point on the perimete arm. In order that the lamp may be removed when desired the bottom of the housing is hinged at the back and is hel in place by a latch on either side. To prevent overheatin the housing is well ventilated by specially designed light tight ventilators—four in the sloping roof of the lamp hous and four on each of the sides at the bottom.

Provisions are made in the construction of the lamp-hous

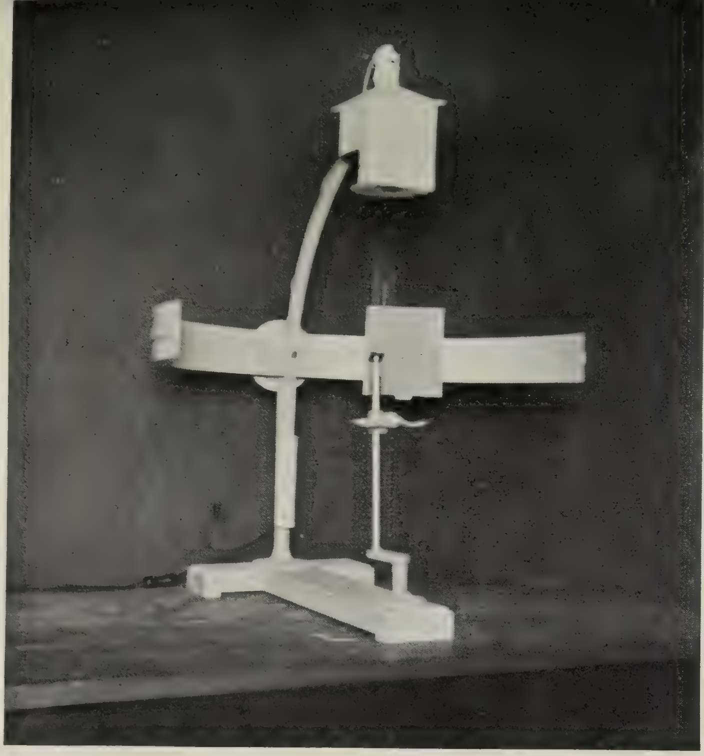

Fig. 2.

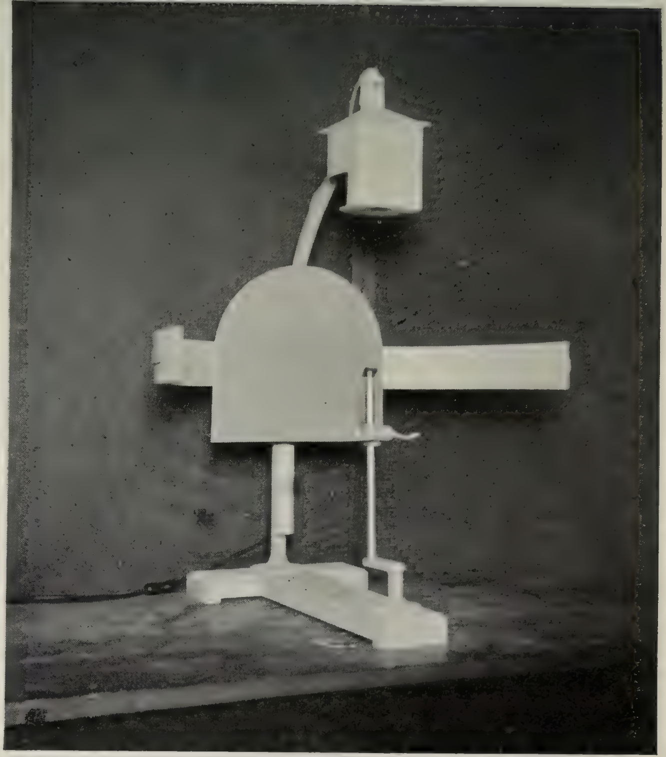

Fig. 3.

for filtering the light to daylight quality. A well-seasoned type C Mazda lamp, operated by ammeter and rheostat control, is used as the source of light. The instrument is designed to run on any 110-volt circuit. In order that the lamp-cord which connects the lamp with the line shall be well out of the road and shall not interfere with the rotation of the perimeter arm, it passes up through the hollow stem which supports the perimeter arm to two copper brushes fastened to a small hard-rubber base 2¾ by ¾ inches at the top of the stem. These brushes are in contact with two circular, insulated metal strips on the back of the brass disc to the face of which is fastened the perimeter arm. From these strips the circuit is continued to the lamp by two insulated wires which thread in and out of the short braces which reënforce the lamp arm.

This perimeter is not difficult to construct or to operate. It provides for a uniform illumination of the perimeter arm in all meridians with light of a good intensity and quality; and with it a precision of control is possible which is comparable with the work of the physical laboratory. Of the two instruments proposed, it is without doubt much the more feasible, and it is also very probably the more correct in actual practice. Both instruments are correct in theory.

(2) *The Brightness of the Preëxposure and the Surrounding Field.*—The brightness of the surface to which the eye is preëxposed may change the apparent limits in certain meridians as much as 17° to 20°. A preëxposure lighter than the color gives a dark, and one darker than the color a light, after-image. These after-images change profoundly the saturation of the color sensation, also its hue. A background or surrounding field lighter or darker than the color produces a similar effect on the limits, but not so great. In this case the disturbing chromatic effect is due to physiologic induction or contrast. The variable effect of brightness of preexposure and of surrounding field can be eliminated only by

making both a gray of the same brightness as the stimulu color. Here again a precise control of the intensity of th illumination for all points of the perimeter arm becomes im portant. That is, the shade of gray which is needed to matc the color in brightness changes with change of illuminatior therefore the selection of a gray which will match the colc in brightness for all points of work presupposes constanc and uniformity of illumination. A further advantage i gained by making the background of the same brightnes as the color. That is, when color and background are of th same brightness, the stimulus disappears completely whe the limit of sensitivity to that color is reached, instead c turning into a gray concerning the colorlessness of whic the patient is apt to be in doubt. This gives the effect c the disappearance type of photometer, and like it, add greatly to the ease and certainty of making the judgmen

The control of brightness of preëxposure and surroundin field is provided for in the perimeter shown in Fig 2 as fo lows: To the stimulus carriage is attached an aluminur holder, No. 19 B. and S. gage, grooved to hold a card 5 b 6 inches. These cards are covered on one side respectivel by grays of the brightness of the four colors, red, yellow green, and blue of the Hering standard series of pigmer papers, as seen in the peripheral retina. At the center c each of these cards is pasted a disc of the appropriate colo subtending a visual angle of 1°. To provide for the contr of the preëxposure for the stationary method of giving th stimulation, cards identical with the background cards ar provided, covered also on one side with a gray of the bright ness of the color. The stimulation is given by this metho as follows: The stimulus is placed at the point to be teste and covered with the preëxposure card. The observer i told to take his fixation. At a given signal the stimulus i uncovered for one second and recovered. In case the movin

stimulus method is used the surrounding field serves also as the preëxposure.

The perimeter arm and body are painted gray, of a shade which is approximately mid-gray to the blue and yellow, the darkest and lightest of the stimuli employed. In our own laboratory the perimeter is used on a table painted with the same gray and stands before a gray screen. These latter precautions, however, are not necessary.

When the perimeter is supplied to the profession, provision will be made that the stimulus and preëxposure cards, a seasoned lamp, and all other perishable parts can be purchased in the quantities desired.

(3) *The Accuracy and Steadiness of Fixation.*—All are familiar with the disturbing effect of inaccuracy and unsteadiness of fixation. If correct and reproducible results are to be obtained, the eye must be accurately placed at the center of the sphere, in the surface of which lies the perimeter arm, and the line of sight must not shift from the fixation-point while the color observation is being made. As an aid to the correct placement of the eye and a check on its steadiness of fixation, a small circular mirror is used as a fixation object, in which the observer sees the image of his own eye. When the eye is correctly placed with the line of sight normal to the surface of the mirror at its central point, the fact is indicated to the observer by the position of the image of his pupil and iris as seen in the mirror. Not only is this simple device of service in determining the correct position of the eye, but it aids the observer greatly in holding a steady fixation.

However, while the image in the mirror will indicate to the observer when the line of sight is normal to the surface of the mirror at its central point, there are two important features in the correct adjustment of the eye over which it exercises no control: (*a*) The distance of the eye from the mirror, and (*b*) the agreement of the meridians of the field

of vision as read on the perimeter with the meridians of the retina. In order that it may be known when the eye is at the correct distance from the perimeter arm, a light measuring rod 33 cm. in length is provided, to one end of which is fastened at right angles a small metal disc. In making the adjustment for distance one end of this rod is placed against the mirror at its center, and the distance of the observer's eye is changed until the closed lid is just in contact with the metal disc. Perhaps the simplest device for insuring a constancy of relation of the meridians of the retina to the meridians of the field of vision, as laid off by the perimeter arm, in other words, for guarding against a slight tilting of the head to one side or the other, is a mouth-bit. We have designed a mouth-bit of light wood to be changed for each observer, so shaped that it cannot be bitten too far forward or back, and thus the distance of the eye from the mirror be changed, or too far to one side or the other.

In order quickly and conveniently to locate the patient's eye at the center of the perimeter system, three adjustments are provided: a rack and pinion to raise or lower the head, a second rack and pinion to shift the head to the right or left, and a coarse screw adjustment to change the distance of the eye from the perimeter arm. In the process of getting the eye in position the patient bites the mouth-bit, the eye is brought to the level of the mirror with the first rack and pinion, its image is centered in the mirror with the second rack and pinion, and its correct distance from the mirror is obtained by means of the screw adjustment and the measuring rod already referred to. Once these adjustments are made for an eye they need not be made again during the process of taking the fields for that eye; that is, the re-biting of the mouth-bit guarantees that the eye always returns to the same position for which the original adjustments were made. These adjustment devices were not completed in time to be shown in Figs. 2 and 3.

The steadiness of fixation is greatly influenced by the method of giving the stimulation. One of the serious objections to a moving stimulus is the difficulty of holding a steady fixation while the object to be observed is moving. The alternative procedure is the use of a stationary stimulus. That is, the stimulus is placed at the desired point on the perimeter arm and covered with the preëxposure card. The observer takes his fixation, and at a given signal the stimulus is exposed and re-covered. By this method of giving the stimulation more time is consumed, but a much greater precision of result is possible. A compromise procedure is recommended. That is, the approximate location of the limit is determined with the moving stimulus and the exact location with the stationary stimulus. By this compromise but very little more time is required and there is no sacrifice of precision.

In order to provide for the mapping of the normal blind spot and for the quick detection and mapping of central and paracentral scotomata, it has been deemed advisable to add to the perimeter recommended a tangent screen subtending a visual angle of 60 or more degrees. Provision is made so that this screen can be quickly and conveniently attached to the stimulus carriage and moved into position. Cards of white or black, as may be desired, with the field laid off on the tangent scale, are provided for mapping the area deficient in the light sense, and of grays of the brightness of the colors for mapping the color deficiencies. This is shown in Fig. 3.

With the controls provided in the perimeter recommended a careful worker can without difficulty reproduce the limits of sensitivity within one or two degrees.

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FACTORS WHICH INFLUENCE THE COLOR SENSITIVITY OF THE PERIPHERAL RETINA.

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(By invitation.)

Introduction.—The difficulty of getting reproducible results in determinations of the color sensitivity of the peripheral retina is a common complaint among laboratory and clinic workers. The actual distribution of retinal sensitivities is only one of the factors which influence the results of the perimetric or campimetric determination. By varying the conditions under which the work is done the fields of color sensitivity, beyond a certain degree of eccentricity, may be made to have almost any extent within the limits of the field of vision, and to vary radically in shape.

The difficulty of obtaining reproducible results is so great as to lead many seriously to question the value of the perimetric or campimetric determination in the work of diagnosis. Their value in diagnosing and checking up the course of some of the most serious affections of the eye is readily conceded, however, provided the needed precision can be obtained. The need of greater precision of work in the laboratory, while less important to human welfare, is no less insistent. These combined needs led us several years ago to make a study of the variable factors which influence the chromatic response, the details of which are still in progress. Some of these factors pertain to the control of the stimulus; some are peculiar to the response of the eye itself. All may be standardized and controlled. The normal eye is highly sensitive and complex in its responses, but not inherently erratic.

While the abnormal eye may be more erratic,—one of the symptoms, it may be, of its abnormality,—there should be, so far as we can see, no essential difference in the technic of the testing and study of its functioning.

The variable factors which influence the apparent limits of color sensitivity are the wave-length and purity of the stimulus, the intensity of the stimulus and the visual angle, length of exposure of the eye, the method of exposure (moving or stationary stimulus), accuracy and steadiness of fixation, the intensity of the general illumination of the retina and its state of adaptation, breadth of pupil, and the brightness of the preëxposure and of the background or surrounding field. Only a few of these can be considered here. For the fuller treatment a bibliography is appended. The most important of these factors, from the standpoint of the work of the office and clinic, are perhaps the intensity of the stimulus and the precision of its control, the brightness of the preëxposure and of the surrounding field, the intensity of the general illumination, and the accuracy and steadiness of fixation.

The Intensity of the Stimulus.—By a sufficiently wide variation in this factor alone the fields of color sensitivity may be made to have almost any breadth within the field of vision, and to differ radically in shape. With very high intensities the limits of red, yellow, and blue are coincident with the limits of white light vision. Green cannot be made to have so wide an extent. With stimuli of medium intensities of equal energy the limits of red, blue, and yellow interlace or criss-cross. The limits for green again are narrower. The conventional clinic rating of limits from widest to narrowest in the order blue, red and green is, with the exception of green, a function of the relative intensities of the stimuli employed. A decrease of intensity of the stimuli not only narrows the limits but, because of the irregular distribution of sensitivities in the different meridians, causes a marked

change in the shape of the fields of sensitivity. Without great precision in the control of intensity, it is obvious that reproducibility of result cannot be obtained and little significance can be attached either to extent or shape of the fields of sensitivity or to variations from time to time or from person to person in these important features.

The effect of changes in the intensity of the stimulus, both on the extent and shape of the color fields, varies with the order of magnitude of intensity employed. For medium and low intensities the effect of a given amount of change s very much greater than for high intensities. This is an obvious corollary of the type of distribution of sensitivities ound in the peripheral retina. That is, in passing from the enter toward the periphery the decrease in sensitivity is omparatively slow and gradual in the paracentral retina, t is much faster and more abrupt in the mid-periphery, and ery abrupt in the far periphery. It requires, therefore, omparatively large changes of intensity in stimuli of high ntensity, which carry the limits of sensitivity into the far eriphery, to produce a significant change in the limits; not o great a change in stimuli of medium intensity; and a still naller change in stimuli of low intensity. This effect varies reatly, however, for the same color in the different meridins, and for different colors in the same meridian. For imuli of the medium and low intensities used in the office nd clinic the effect of change of intensity is very marked deed both on the extent and shape of the fields of sensivity.

The Chromatic Thresholds of Sensation from Center to eriphery of the Retina.—In order to show the irregularity decrease in sensitivity in passing from the center toward e periphery of the retina, we have determined the threshold he amount of light required just to arouse the color sensaon) for the different colors in the different meridians. A aphic representation of the results of these determinations

for two meridians—the temporal and nasal—is given i Charts I–IV. In these charts the degree of eccentricity i plotted along the horizontal coördinate and the energy o intensity values of the threshold in watts (10^7 ergs per second are plotted along the vertical coördinate. The representa tion is retinal, not field of vision. In case of red, yellow, an blue, it will be remembered from statements made earlier i the paper, the limits of sensitivity for lights of high intensi ties coincide with the limits of white light vision. This however, was not the case for the green stimulus. By n increase of intensity were we able to make the limits of gree sensitivity coincide with the limits of white light vision.

In Charts III and IV the above values from the center o the retina through the region of gradual decrease of sensi tivity are plotted on a larger scale. This was done becaus when plotted on the scale used in Charts I and II, the curve fall so closely together that the relative sensitivities to th four colors are not clearly represented. That is, the rang of values for the threshold from the center to the extrem periphery of the retina is so great that in Charts I and II, i which the entire range is represented, a scale value had t be chosen for the vertical coördinate, which is so large a almost to obscure the smaller differences in relative sensi tivity to the different colors in the paracentral retina, th region of gradual decrease in sensitivity.

Space cannot be taken here for a full discussion of th results of these determinations. For a more detailed state ment of results and a fuller discussion of their bearing o points of theoretic and practical importance, the reader i referred to "Chromatic Thresholds of Sensation from Cente to Periphery of the Retina and Their Bearing on Color The ory," Psychol. Review, 1919, xxvi, pp. 16–42; 150–163 The following points, however, may be noted in connectio with the present paper:

(*a*) Among other things, the foregoing charts show th

great irregularity in the decrease of sensitivity to each color which is found in passing from the center to the periphery of the retina. This irregularity, moreover, differs greatly in the different meridians. From these irregularities it is

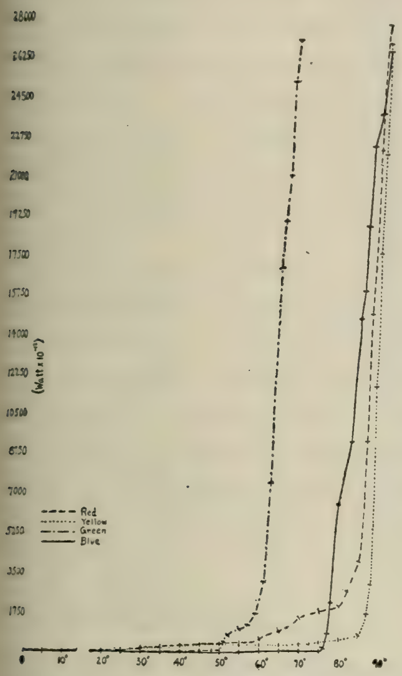

Chart I.—Chromatic thresholds for the four colors, nasal meridian. In this chart degree of eccentricity in the retinal field is plotted along the horizontal coördinate and the energy or intensity value of the threshold is plotted along the vertical coördinate. The threshold values are in terms of total energy entering the eye.

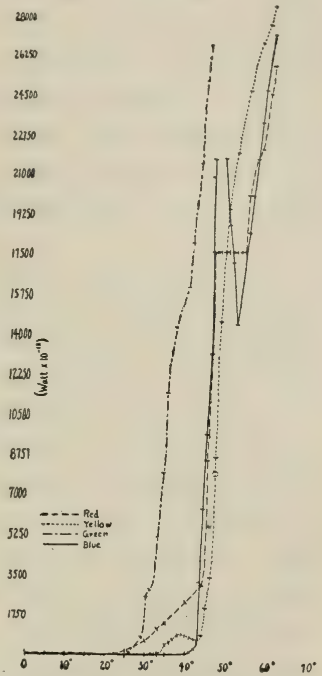

Chart II.—Chromatic thresholds for the four colors, temporal meridian.

obvious why the shape as well as the extent of the fields of sensitivity changes with the change of intensity of the stimulus light. That is, depending upon the different rates of decrease of sensitivity in the different meridians, a given increase or decrease of intensity of the stimulus light causes

respectively different amounts of extension or contraction of the fields in these meridians. The result is, of course, a change of shape of the field proportionate to the amount of

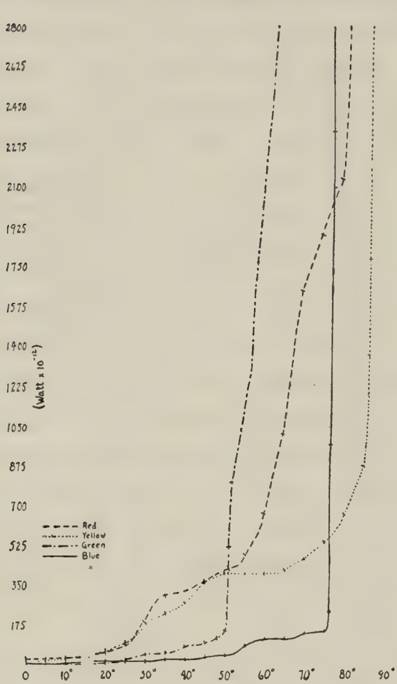

Chart III.—Chromatic thresholds for the four colors, nasal meridian. In this chart and Chart IV the values represented in Charts I and II respectively, from the center of the retina through the region of gradual decrease of sensitivity, are plotted on a larger scale. This is done because when plotted on the scale used in Charts I and II, the curves fall so closely together that the relative sensitivities are not clearly represented.

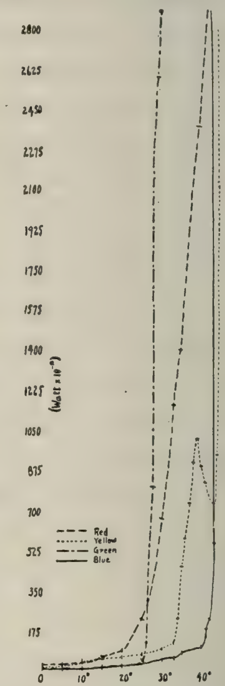

Chart IV.—Chromatic thresholds for the four colors, temporal meridian.

irregularity of the distribution of sensitivity in the different meridians.

(*b*) A further obvious corollary of irregularity of distribution of sensitivity in the different meridians is the interlacing

or criss-crossing of the limits when the stimuli are so graded in intensity as to give the limits for all the colors approximately the same degree of eccentricity. That is, a condition of coincident or concentric limits would presuppose regularity of distribution of sensitivity from meridian to meridian; irregularity inevitably leads to an intersection or criss-crossing when the conditions under which the determinations are made are such that the fields of sensitivity have approximately the same breadth. A frequent criss-crossing of the limits, it will be noted in Fig. 4, occurs for red, yellow, and blue when stimuli of medium intensity and equal energies are used.

(*c*) A third point which may be noted in passing is the correspondence of the changes in the hue of red and green, in passing from the center to the periphery of the retina, with the relative distribution of sensitivities to red, green, and yellow. That is, the red and green wave-lengths of light have the power to arouse not only the sensations of red and green, but also weakly the sensation of yellow. In the center of the retina, which is fully sensitive to red and green, the weakly aroused yellow sensation is below the threshold, *i.e.*, too weak to be sensed in the presence of the strongly aroused red and green sensations. However, in those parts of the periphery of the retina in which the loss of sensitivity to red and green is greater than to yellow, the yellow component of the sensation comes above the threshold and the red and green stimuli are sensed as yellowish-red and yellowish-green. For example, in passing from the center to the periphery of the retina in the nasal meridian, the red stimulus was sensed as red from the center to about 60°; from 60° to about 86° it was sensed as yellowish-red or orange; from 86° to the limits of sensitivity it was sensed again as red. Corresponding to this it will be noted that there is in this meridian a fairly close agreement in sensitivity to red and yellow from the center to about 60° (stimu-

lus sensed as red), at which point there is a relatively sharp decrease in sensitivity to red. That is, from 60° to 86° there is much less sensitivity to red than to yellow (stimulus sensed as yellowish-red or orange). At about 86° there is a sharp decrease in sensitivity to yellow, and from this point on to the limits, a fairly close agreement again in sensitivity to the two colors (stimulus sensed as red). In the temporal meridian the red stimulus was sensed as red from the center of the retina to about 30°; from there to about 47° as yellowish-red or orange; and from 47° to the limits of sensitivity, as red. Similarly in this meridian there is a fairly close agreement in sensitivity to red and yellow from the center to about 30°; from 30° to about 47° there is a considerably greater sensitivity to yellow than to red; and from this point on to the limits greater sensitivity to red than to yellow. In case of green in the nasal meridian the greater loss in sensitivity to green as compared with yellow begins at about 51°; and in the temporal meridian at about 26°. Correspondingly at these points the green stimulus began to be sensed as yellowish-green and continued to be sensed in this hue until the limits of sensitivity to green were reached, from which point on for a short distance it was sensed as unsaturated yellow.

These changes of hue are the normal changes for spectrum or pure red and green in passing from the center to the periphery of the retina when there is no achromatic effect of preëxposure and surrounding field, that is, when the preëxposure and surrounding field are a gray of the same brightness as the color and when the general illumination of the room is held constant. Later in the paper the changes produced by a preëxposure and surrounding field lighter or darker than the color and by a variable illumination will be given.

In Chart II, temporal meridian, a gap will be noted in the curve for blue not present in the curves for the other colors.

In this area is represented a peculiar type of color-blindness, small areas or spots of which are found, so far as we have been able to discover, in all or most peripheral retinas. In these spots the blindness is to one color alone. The spot is fully sensitive to all of the other colors. Moreover, it shows no deficiency in the canceling and after-image and contrast reactions of the color in question. That is, in this area the stimulus, although it is not sensed as color, has just as much power to cancel the complementary color and to arouse the after-image as it has in the immediately surrounding retina. These spots seem not to be subject to change and apparently are not pathologic. An examination of a large number of observers show that eyes may differ widely with regard to the number and size of these spots, their location and the color affected. A successful search of the peripheral retina for the presence of such spots requires a means of making a rather minute investigation of the retina from center to periphery in a number of meridians. A more detailed report of the study of this phenomenon may be found in "Some Areas of Color Blindness of an Unusual Type," Jour. of Exper. Psych., 1917, ii, pp. 295–324. F. Schumann: "Ein ungewöhnlicher Fall von Farbenblindheit," Bericht über den I. Kongress für experimentelle Psychologie in Giessen, 1904, pp. 10–13, reports a case (his own) in which the whole retina is affected by this type of color blindness.

Conditions Under Which the Thresholds were Determined.—The determinations were made under the following conditions: (1) The colored lights were taken from the spectrum. There are two reasons for this in an investigation of the kind here undertaken: (*a*) The stimuli should be as homogeneous as possible with regard to the visible wave-lengths. The presence of alien visible wave-lengths affects the results of a determination of chromatic sensitivity in two ways. Through physiologic inhibitions and interactions it decreases the amount of the color response; and it increases the energy

measurement. In both of these ways the value of the threshold is raised by the presence of impurities in the stimulus light. And (*b*) the stimuli should be free from the infrared and ultra-violet radiations which would affect the thermopile used to measure the intensity of light, but not the eye.

The stimuli employed were a narrow band of red in the region of 670 $\mu\mu$; of yellow in the region of 581 $\mu\mu$; of green in the region of 522 $\mu\mu$; and of blue in the region of 468 $\mu\mu$. The breadth of analyzing slit used in isolating these bands was maintained constant at 0.5 mm. The ranges of wave-lengths obtained were approximately 660–680 $\mu\mu$; 575–587 $\mu\mu$; 518–526 $\mu\mu$; and 468–474 $\mu\mu$. The spectrum was gotten and the different wave-lengths were presented to the eye by means of our apparatus described in the *Journal of Experimental Psychology*, 1916, i, pp. 247–284: "A Spectroscopic Apparatus for the Investigation of the Color Sensitivity of the Retina, Central and Peripheral." In every case the light was examined for impurities at the analyzing slit by means of a small Hilger direct vision spectroscope provided with an illuminated scale. When found, impurities were absorbed by thin gelatins selected so as to cut out as little as possible of the useful light. These gelatins were placed over the analyzing slit and were held in position by short clips fastened to the front surface of the jaws the edges of which formed the slit.

(2) The determinations of the threshold were made in energy terms. Measurements were made at two places: at the analyzing slit and at the eye. In making the threshold determinations it was found convenient first to make the colors all equal in energy value. The reductions needed for this equalization were made by appropriate adjustments of the collimator slit. Since the blue represents the smallest amount of energy of any of the colors employed, they were all made equal in energy to the blue of the spectrum used,

namely, the prismatic spectrum of a Nernst filament operated by 0.6 ampere of current. From this intensity they were reduced to the threshold by means of the especially constructed sectored discs described in a former paper,* and the energy values computed from the simple law of the disc. The method of making the energy measurements by means of a thermopile has been described in previous papers.†

(3) The field surrounding the stimulus and the preëxposure were always maintained as nearly as possible at the same brightness as the stimulus at the threshold value of sensation. These surfaces were made from the Hering standard gray papers. It was found to be necessary to change the brightness of the surrounding field and preëxposure frequently for each stimulus because the brightness value of the color at the chromatic threshold changed quite rapidly from center to periphery of the retina. There were two causes for this change: (*a*) The intensity of light had to be increased a very great deal from center to periphery to give the chromatic threshold from point to point; and (*b*) the achromatic value of the colors does not remain the same from the center to the periphery of the retina (the Purkinje shift of the peripheral retina). The gray that matched the stimulus in achromatic value at each point was determined by the equality of brightness method. The match was made in every case for the point of the retina under investigation. In order to make the specification of the brightness of the preëxposure and the surrounding field independent of the illumination of the room and of the variability of the reflection coefficients of different issues of Hering papers, the

* Journal of Experimental Psychology, 1916, i, pp. 271–274.

† Radiometric Apparatus for Use in Psychological and Physiological Optics, Psych. Rev. Monog., 1917, xxiv, 66 pp. +xvi; Chromatic Thresholds of Sensation from Center to Periphery of the Retina, Part I, Psych. Rev., 1919, xxvi, pp. 16–42; Selectiveness of the Achromatic Response of the Eye to Wave-length and Intensity of Light. Studies in Psychology, Titchener Commemorative Volume, Published by L. N. Wilson, Worcester, Mass., 1917, pp. 280–307.

brightness was in each case determined in candle-power per sq. in.

(4) The illumination of the room was kept at a constant value. Two features are necessary for this control: (*a*) A means must be had of detecting small changes of illumination. This may be accomplished by a portable photometer of the Sharp-Millar or Macbeth types, furnished with a daylight screen, or of the simpler type described by the writers in a previous paper.* And (*b*) a means must be had also of producing small variations in the illumination of the room, else the changes due to fluctuations in the external light can not be compensated for with the precision and minuteness of control that is needed. This is accomplished in our optics rooms† by two systems of thin white curtains running on spring rollers beneath the skylight. Large changes are produced by a light-proof curtain. One of the systems of white curtains and the light-proof curtain run lengthwise of the room; the other system of white curtains runs across the room. By means of the white curtains either small local or small general changes can be produced in the illumination of the room; and by means of the light-proof curtain larger changes may be produced ranging from full illumination to the darkness of a moderately good dark room. The light-proof curtain is of a breadth equal to that of the room and runs in a light-tight boxing. The white curtains are narrower and are made to overlap at the edges. These latter curtains run on wire guards so distributed as to prevent sagging or wrinkling. Above these curtains are pivoted two large diffusion sashes of glass ground on one side completely filling the skylight opening. These sashes diffuse the light

* A Simple Daylight Photometer, Amer. Jour. Psych., 1916, xxvii, pp. 335–340.

† An Optics Room and a Method of Standardizing Its Illumination, Psych. Rev., 1912, xix, pp. 364–373; A Method of Standardizing the Color Value of the Daylight Illumination of an Optics Room, Amer. Jour. Psych., 1920, xxxi, pp. 77–87.

in the room giving an even distribution of illumination and rendering, because of that fact, an even and precise control easier to accomplish. In a careful specification of the conditions under which the work is done, a very important item is to give a photometric specification of the illumination of the room. This may be done in foot- or meter-candles as desired. If the illumination is uneven it should be done systematically throughout the room. If, on the other hand, it is pretty uniform, it is usually sufficient to give its value in three or more directions at the point of work. In case of the present work, for example, the value of the horizontal component was 30.49 foot-candles; the vertical component, 121.95 foot-candles; and the 45° component, 82.97 foot-candles.

(5) The results were made independent of the size of the pupil. Breadth of pupil affects the results of a determination of the sensitivity of the peripheral retina in the following ways: It influences the clearness of imaging, the amount of light entering the eye, and, by limiting the angle at which the beam of light may enter the eye, the degree of eccentricity at which an image may be formed on the retina. Independence of change in size of pupil was especially needed in this work because of the large variations in the intensity of light used. Such control is very easy to accomplish with the means of presenting the light to the eye that is used in our spectroscopic apparatus. All that is needed is to keep the image that falls on the pupil of a constant size and smaller than the pupil throughout its entire range of variations in the given series of experiments. Not only can this variation be determined in preliminary experiments as a guide to the size of image that is needed, but the image itself can be compared with the pupil at each observation. For details of the method of exercising this control, see "A Substitute for an Artificial Pupil," Psych. Rev., 1916, xxiii, pp. 380–383.

The Effect of Variations of the Intensity of the Stimulus on

the Breadth of the Color Fields.—Only the results obtained with stimuli of very high intensities will be given in this paper. In later work the effect of variations of intensity on the size and shape of the color fields will be given for stimuli of medium and low intensities.

Five intensities of light were used, the prismatic spectrum of a Nernst filament operated by 0.6 ampere of current, Intensity A; the colors of this spectrum reduced to 1/32 of their original intensity, 1/32 A; an equal energy spectrum in which the four colors were all made equal in intensity to the blue (the color of least energy) at intensity A, intensity B; the colors of this spectrum reduced to 1/32 of their original intensity, intensity 1/32 B; and the standard Hering pigments red, yellow, green and blue illuminated by 390 foot-candles of light, vertical component. The fields for these stimuli are given in Figs. 1–5.

The energy values of the red, yellow, green, and blue wave-length at intensity A were respectively 9096.639, 4065.624, 1562.388, and 882.025 watt x 10^{-10}; at intensity B, 891.05, 882.51, 884.946, and 882.025 watt x 10^{-10}. These intensities were much greater than were needed to make the limits of red, yellow, and green coincide with the limits of white light vision. This fact should, therefore, be borne in mind in considering how much the limits were narrowed by reducing the intensity to 1/32 A and 1/32 B. That is, the narrowing of the limits shown in Figs. 1–4 was produced by only a small part of each of these reductions, as may be seen by comparing the following values of the threshold at the limits of white light vision with the intensity values of 1/32 A and 1/32 B. The energy values of the threshold in the nasal meridian at the limits of white light vision were for red, yellow, and blue respectively 227.836, 268.95, and 264.368 watt x 10^{-10}; in the temporal meridian, 258.93, 285.25, and 272.428 watt x 10^{-10}. The energy values for red, yellow, and blue at intensity 1/32 A were respectively 284.27, 127.051,

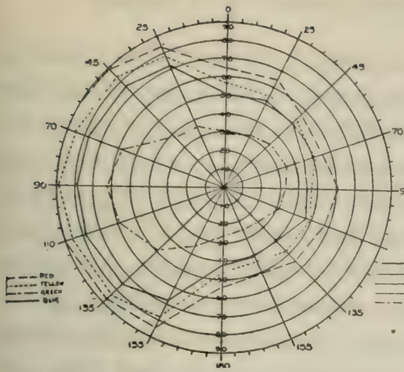

Fig. 2.—The effect of intensity of stimulus on the limits of sensitivity, prismatic spectrum. In this chart are represented the limits of sensitivity for intensity 1/32 A: red, 284.27, yellow, 127.051, green, 48.825, and blue, 27.563 watt × 10^{-10}.

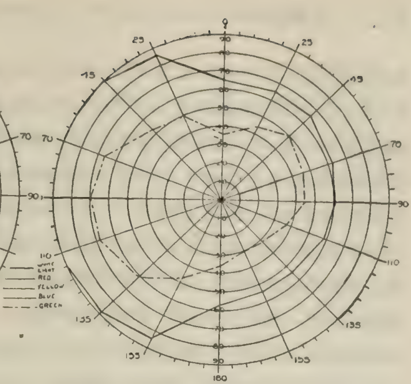

Fig. 1.—The effect of intensity of stimulus on the limits of sensitivity, prismatic spectrum. In this chart are represented the limits of sensitivity for intensity A: red, 9096.639, yellow, 4056.624, green, 1562.388, and blue, 882.025 watt × 10^{-10}. In Figs. 1–5 the representation is retinal, not field of vision.

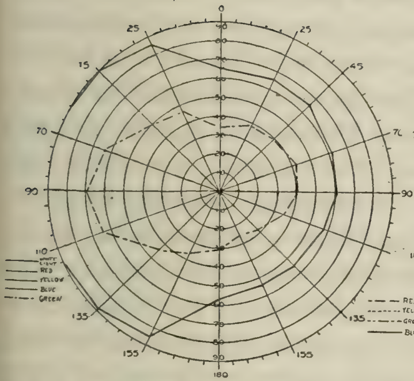

Fig. 3.—The effect of intensity of stimulus on the limits of sensitivity, equal energy spectrum. In this chart are represented the limits of sensitivity for intensity B (equated in energy to the blue, intensity A): red, 891.05, yellow, 882.51, green, 884.946, and blue, 882.025 watt × 10^{-10}.

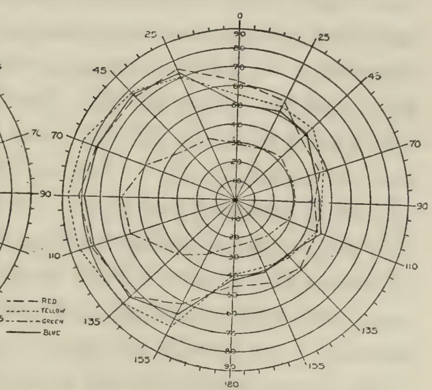

Fig. 4.—The effect of intensity of stimulus on the limits of sensitivity, equal energy spectrum. In this chart are represented the limits of sensitivity for intensity 1/32 B: red, 27.845, yellow, 27,578, green, 27,655, and blue, 27.563 watt × 10^{-10}.

and 27.563 watt x 10^{-10}; at intensity 1/32 B, 27.845, 27.578, and 27.563 watt x 10^{-10}. At intensity 1/32 A, therefore, the red was not reduced to its threshold value at the limits of white light vision; the yellow a little more than 1/2, and the blue not greater than 1/10 of this value; at intensity 1/32 B all these stimuli were reduced not quite to 1/10 of their threshold value at the limits of white light vision. A more detailed and exact knowledge of the effect of change of intensity on the limits from center to periphery of the retina in the temporal and nasal meridians may be had from an examination of the threshold curves in Charts I and II. In these curves the effect of 22–26 changes of intensity are shown for the nasal meridian, and 19–29 changes for the temporal meridian. That is, the threshold values are given for that number of points respectively in these two meridians, selected and spaced with special reference to the steepness or pitch of the sensitivity gradient. An inspection of these charts shows that in the nasal meridian from the center of the retina to 85°, only very small reductions of intensity are required to narrow the limits for yellow by significant amounts; for blue this region extends to 75°; for red to 60°–85°; and for green to 50°. In the temporal meridian it extends for yellow to 35°–45°; for blue to 40°; for red 25°–40°; and for green to 25°. Beyond these points sensitivity falls off much more abruptly, *i. e.*, much larger changes of intensity are required to produce significant changes in the limits.

Conditions Under Which the Limits were Determined.—The spectrum was obtained and the different wave-lengths presented to the eye by means of the same apparatus employed in the preceding threshold determinations. The stimuli were again narrow bands of red, green, yellow, and blue in the regions respectively of 670 $\mu\mu$, 581 $\mu\mu$, 522 $\mu\mu$, and 468 $\mu\mu$. The control of purity, intensity, brightness of preëxposure and surrounding field, general illumination, breadth of pupil, etc., also were so nearly identical with those described in

connection with the threshold determinations that space will not be taken for their further discussion here.

The stimulus used was the circular aperture of the campimeter (rotary), 15 mm. in diameter, filled with light by the focusing lens. At a distance of 25 cm. from the pupil of the eye, on which the light from the objective slit of the spectroscope was focused, this aperture subtended a visual angle of 3° 26′. The time of exposure was one second and the interval between exposures varied between three and five minutes, depending upon circumstances and the need for precautionary measures. If the stimulus was sensed in its proper color at any time during the one second interval of exposure, the retina was called color sensitive at that point. (At the limit of white light vision the red stimulus, for example, of the intensity used was sensed as a tint of red.) The field in the 16 meridians was always mapped for one color before the work on another color was begun. The maps shown in Figs. 1–5 represent points on the retina, not field of vision.

For a fuller statement and discussion of the conditions under which the work was done and a detailed statement and discussion of results the reader is referred to "The Absolute Limits of Color Sensitivity and the Effect of Intensity of Light on the Apparent Limits," Psych. Rev., 1920, xxvii, pp. 1–23.

The Brightness of the Preëxposure and the Surrounding Field.—The brightness of the surface to which the eye is preëxposed may change the apparent limits in certain meridians as much as 17°. A preëxposure lighter than the color gives a dark after-image; a preëxposure darker than the color gives a light after-image. These after-images change profoundly the saturation of the color sensation, also its hue. In a given series of experiments in which all other factors were carefully controlled the limits for red were narrowed by a white preëxposure by amounts varying in the different meridians from 4°–15°, for yellow 2°–17°, for green 3°–15°,

and for blue 4°–12°; by a black preëxposure, red 3°–11°, yellow 3°–10°, green 4°–13°, and blue 2°–12°. In these experiments the surrounding field was a gray of the brightness of the color at the point of investigation, and the results obtained with the preëxposure of a gray of the brightness of the color were taken as the standard in terms of which to estimate the amount the field was narrowed by the white and black preëxposures.

A background or surrounding field lighter or darker than the color produces a similar effect on the limits, but not so great. In this case the disturbing achromatic effect is produced by physiologic induction or contrast. In some meridians the effect of surrounding field alone narrowed the limits as much as 11°. A white surrounding field narrowed the limits in the different meridians for red by amounts ranging from 2°–10°, for yellow 2°–9°, for green 2°–11°, and for blue 2°–10°; the black surrounding field narrowed the limits for red 1°–8°, for yellow 1°–8°, for green 2°–10°, and for blue 2°–9°.

The combined effect of surrounding field and preëxposure is, of course, greater than either alone. A preëxposure and surrounding field of white narrowed the limits for red by amounts varying in the different meridians from 4°–17°, for yellow 5°–12°, for green 7°–18°, and for blue 5°–18°; a preexposure and surrounding field of black narrowed the field for red from 5°–19°, for yellow 2°–20°, for green 4°–20°, and for blue 5°–17°.

The effect of preëxposure and surrounding field on the breadth of the color-fields is shown in Figs. 6–8. Although the effect of both factors has been determined separately for the different colors, a separate graphic representation has not been made for each in this paper. In order to save space only the combined effect of both has been shown, and for only three of the colors—red, green, and blue.

The Intensity of the General Illumination.—The variable

effects both of the preëxposure and surrounding field are strongly influenced by changes in the intensity of the illumination. The results cited above were obtained with a precise control of the intensity of illumination. When the

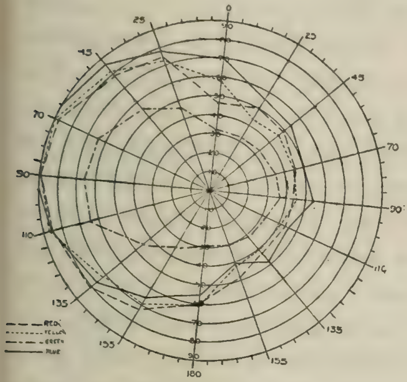

Fig. 5.—The limits of sensitivity to red, yellow, green, and blue of the Hering series of pigment papers, intensity of illumination, vertical component, 390 foot-candles.

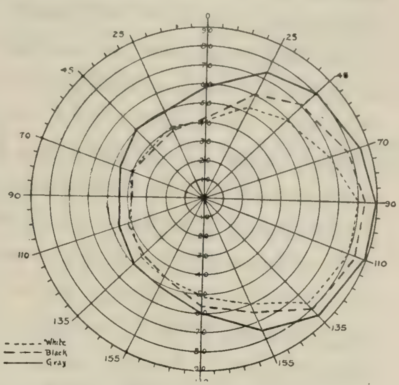

Fig. 6.—The combined effect of brightness of preëxposure and surrounding field on the limits of the color field. In this chart are shown the apparent limits for red with both preëxposure and surrounding field of white, black, and gray of the brightness of the color at the point of investigation.

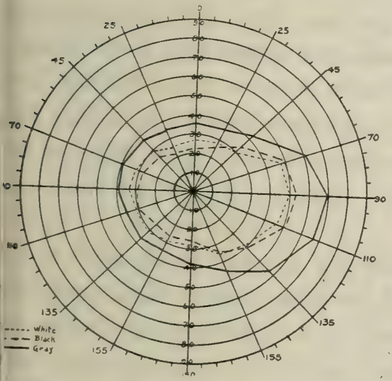

Fig. 7.—The combined effect of brightness of preëxposure and surrounding field on the limits of the color field. In this chart are shown the apparent limits for green with both preëxposure and surrounding field of white, black, and gray of the brightness of the color at the point of investigation.

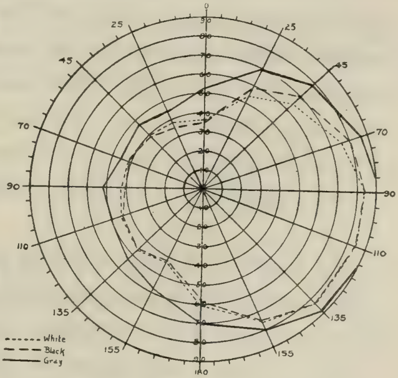

Fig. 8.—The combined effect of brightness of preëxposure and surrounding field on the limits of the color field. In this chart are shown the apparent limits for blue with both preëxposure and surrounding field of white, black, and gray of the brightness of the color at the point of investigation.

results are obtained under such ranges of change of illumination as may occur during the course of a given day or from day to day, the variability in effect is greatly increased, reaching in some meridians as much as 28°–30°. Further important effects of surrounding field as influenced by change of illumination are the changes in hue which the color undergoes in passing towards the periphery of the retina. For example, on bright, dark, and medium days with different brightnesses of surrounding field, the red stimulus may be seen in any of the following hues in passing from the center towards the periphery of the retina: red, red-orange, orange-red, orange-yellow, yellow, and dark red; the green stimulus as green, blue-green, pale blue, and yellow; the yellow stimulus as yellow, orange, orange-yellow, red-orange, and pale yellow. Under some conditions of surrounding field and illumination the color is seen in the central retina in its proper hue, in the mid-periphery in the modified hue, and near the limits again in its proper hue. This is true in particular of red on a dark day with a white surrounding field and of yellow on a dark day with a black surrounding field To those who assign as the limit the first point at which the color is no longer seen in its proper hue, such phenomena would afford considerable annoyance especially if in determining the limit the stimulus were moved from within ou and from without in. In the cases mentioned the limits fo red obtained by the two procedures would have differed i some meridians as much as 24°, and for yellow as much a 59°.

In Figs. 9–19 the effects of such ranges of change of il lumination as are represented by bright and dark days i conjunction with preëxposures and surrounding fields o white, black, and gray of the brightness of the color ar represented. In these maps the effect, both on the breadt of the fields and the hue in which the color was sensed, i represented. That is, not only is the total field mapped fo

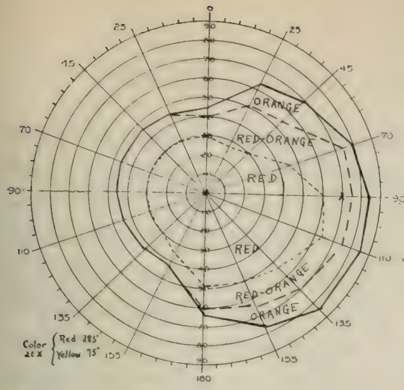

Fig. 9.—Field for red. Bright day, gray surrounding field and pre-exposure.

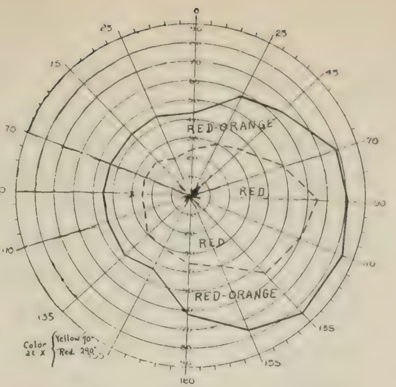

Fig. 10.—Field for red. Dark day, gray surrounding field and pre-exposure.

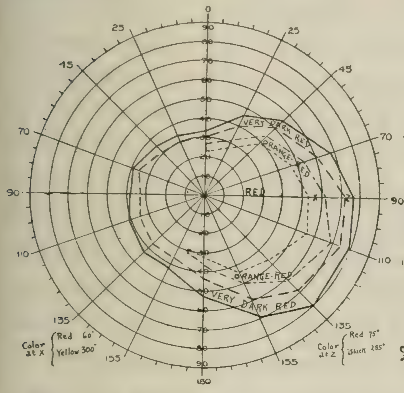

Fig. 11.—Field for red. Bright day, white surrounding field and preëxposure.

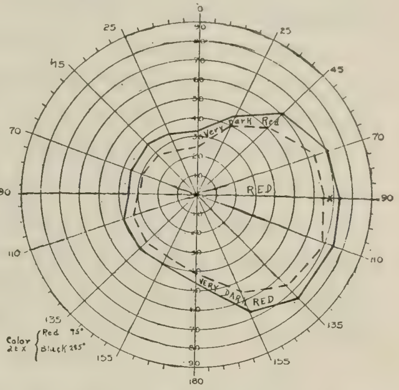

Fig. 12.—Field for red. Dark day, white surrounding field and preëxposure.

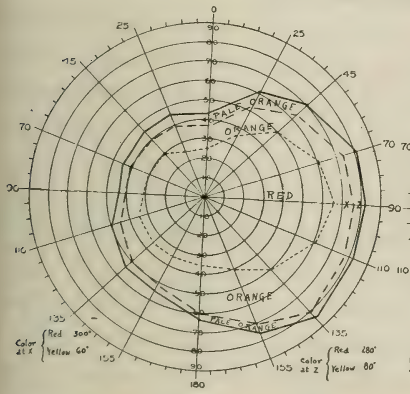

Fig. 13.—Field for red. Bright day, black surrounding field and preëxposure.

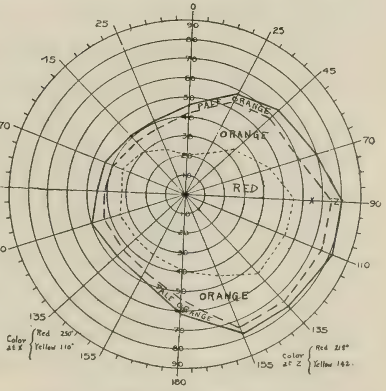

Fig. 14.—Field for red. Dark day, black surrounding field and preëxposure.

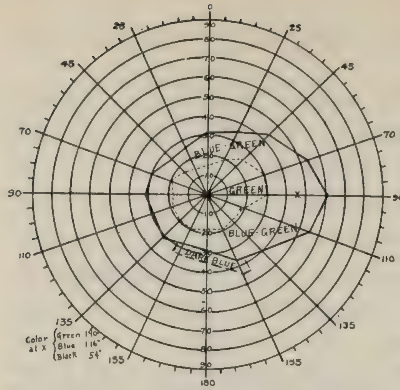

Fig. 15.—Field for green. Bright day, white surrounding field and preëxposure.

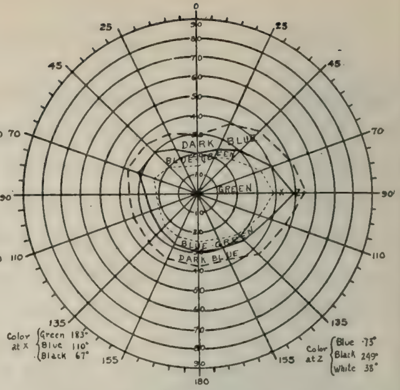

Fig. 16.—Field for green. Dark day, white surrounding field and preëxposure.

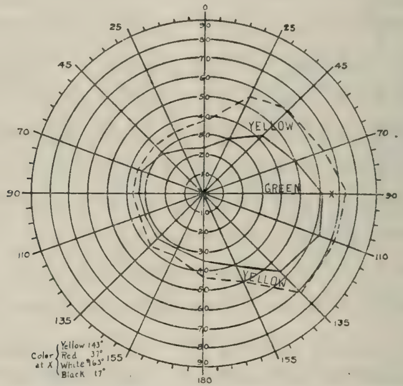

Fig. 17.—Field for green. Bright day, gray surrounding field and preëxposure.

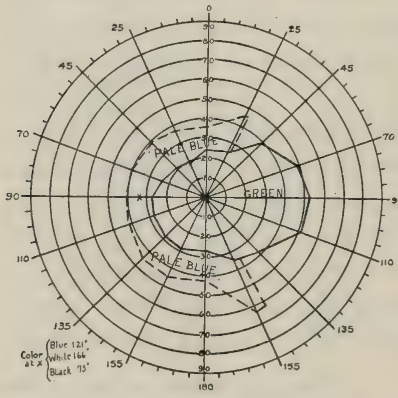

Fig. 18.—Field for green. Bright day, black surrounding field and preëxposure.

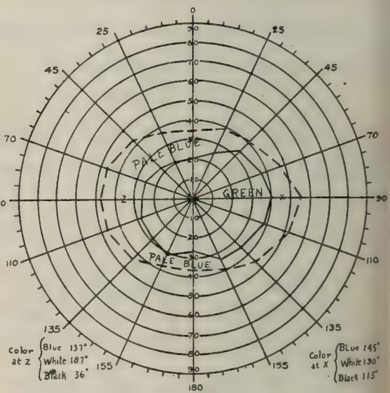

Fig. 19.—Field for green. Dark day, black surrounding field and preëxposure.

each stimulus, but also the subdivisions in which the different hues were sensed. The rotary campimeter, by means of which the fields were taken, was so constructed that the different hues in which the stimulus was sensed at any point in the field could be matched in color and brightness in central vision on a small electric color mixer. The equations representing these hues in terms of the Hering standard colors and white and black are shown in the maps referred to above. Space has been allowed for showing the effect on only two of the colors—red and green.

In order to realize how profoundly the powers of chromatic response must have been affected to change the limits of sensitivity by the amounts represented in the foregoing figures and charts, one must bear in mind how abruptly sensitivity falls off in the far periphery of the retina. A determination of the threshold of color in the nasal meridian with preëxposure and surrounding field of the same brightness as the color shows that for red 173 per cent. more colored light was required just to be sensed at the limits than 5° inside the limits; for yellow, 260 per cent.; for green, 208 per cent.; and for blue, 208 per cent.

In those meridians in which the limits were wide there is a general tendency for the white preëxposure and surrounding field to narrow the limits more than a black preëxposure and surrounding field. In explanation of this effect it should be stated that the amount of inhibition of the chromatic by the achromatic excitation varies with the color, the part of the retina stimulated, and the state of adaptation of the retina. In the central retina at medium and high illuminations white inhibits color more than black. At these illuminations a black preëxposure and surrounding field are, therefore, much more unfavorable than white. At lower illuminations this difference in effect becomes less pronounced. In the far periphery of the retina, the following are some of the conditions which contribute to make black as preëxposure

and surrounding field give the wider limits of sensitivity: (*a*) A condition of low illumination and a state of low illumination adaptation. (*b*) A darkening of all of the colors, particularly of red and yellow (the Purkinje shift of the peripheral retina). This brings the brightness of the color nearer to black than to white; and the stronger relative darkening of red and yellow than of their neutral or colorless preëxposures and surrounding fields increases the contrast and after-image effect for white and decreases it for black. The darkening of red and yellow in passing to the far periphery of the retina is very great. In the nasal half of the retina, with its wide limits, the effect of this darkening on the results of our determinations is, of course, the most pronounced. As colors darken, there is, when a certain point in the process is reached, varying with the color, a tendency for them to lose their saturation very rapidly. (*c*) Achromatic induction increases very strongly with decrease of illumination and, therefore, increases in passing from the center to the periphery of the retina. It increases much faster for white than for black.

In the meridians in which the limits are narrow the situation is more nearly as it is in the central retina. Here the tendency is for the limits to be narrowed more by a black than by a white preëxposure and surrounding field. In some meridians the amount of narrowing is approximately equal for both. Another factor which tends to make the effect more nearly the same in these meridians for all backgrounds and preëxposures is the more abrupt falling off in sensitivity. That is, more effect on sensitivity is required here to change the limits by a detectable amount than is required in those portions of the retina where the sensitivity grades off more slowly.

In conclusion, a word may not be out of place further in explanation of the effect of brightness of the preëxposure and the surrounding field on the limits of color sensitivity.

As has already been indicated, this effect falls under the general heading of the inhibitive or canceling action of the achromatic excitation on the chromatic. In addition to this quantitative action there is also a qualitative effect. That is, the hue of certain colors is changed by the action of the achromatic excitation. This hue change is greatest when the stimuli are blue and yellow. For example, yellow when mixed with black gives for central vision a greenish-yellow which, with the right proportions of components, may become an olive-green; and blue when mixed with white or light gray gives a sensation of reddish-blue or lavender. These actions, both quantitative and qualitative, take place however the achromatic excitations are aroused—by the admixture of white light, by after-image, and by contrast. It may be strikingly and conveniently demonstrated in the following lecture-room experiments:

(*a*) Set up side by side on three color mixers discs made up of 180° of color, *e. g.*, 180° of blue, and 180° respectively of white, gray of the brightness of the color, and black. When mixed, although the eye receives the same amount of colored light from each set of discs, the mixture with black seems to have lost but very little, if any, color; the mixture with white is a lavender with but little color; and the mixture with gray of the brightness of the color, in this case a very dark gray, is less saturated than the mixture with black. When different grays are used the saturation decreases apparently in graded steps as white is approached. The demonstration can be made on a single color mixer by compounding the color disc with white, black, and gray discs of different breadths or radii. When rotated, this gives the effect of a surface made up of three concentric zones or rings one in which the color is mixed with white, one with gray, and the other with black. The demonstration may be made roughly quantitative by determining the proportions of color required to give the chromatic thresholds in black, white, and

the grays; also by determining the proportions of color and white, black, and gray respectively required to give equal saturations.

(*b*) Prepare a preëxposure surface, half white and half black, 60 x 70 cm. Expose the eye fifteen to twenty seconds and project the after-image on a colored surface, *e. g.*, blue, of the same dimensions. The half of the field preëxposed to black will appear a very pale unsaturated lavender, while the half preëxposed to white will be a dark strongly saturated blue, although the eye receives the same amount of light from both halves of the field. As the after-image dies away the two halves of the field become more and more nearly alike in saturation and color tone. If desired, the preëxposure surface may be made of white, black, and a graded series of grays, appropriately arranged. When this is done, the graded loss in saturation due to the different brightnesses of the after-image may be observed. This demonstration also may be made quantitative by finding the threshold of color after the eye has been preëxposed for fifteen to twenty seconds to white, black, and the grays.

(*c*) Prepare contrast discs with narrow rings of color and inside and outside surfaces respectively of black, white, and a gray of the brightness of the color. Set up on color mixers side by side, and rotate to smooth out the margins. The colors are lightened and darkened respectively by contrast induced by the black and white fields. The effect of these achromatic excitations on the hue and saturation of the colors is similar to those obtained in the former experiments. The quantitative features noted above can also be utilized in this demonstration by employing for the contrast ring in each case a gray of the brightness of the color and enough of the color to give the threshold of color sensation when acted upon by the white and black induction. The effects of induction and after-image, it will be remembered, are not nearly so striking in the central as in the peripheral retina.

Much more induction with a given brightness difference between the inducing and the contrast fields, for example, is produced in the peripheral retina, and only a short period of preëxposure (two to three seconds) is required to give a strong after-image with no latent period.

For these reasons it is easy to understand why it is so much more necessary to control the factors of preëxposure and surrounding field in the peripheral than in the central retina. With a given brightness difference between stimulus and surrounding field, the brightness induction is much increased; and the after-image reaction to the preëxposure in the peripheral retina is strong and extremely quick. With a very short preëxposure the after-image flashes out in full intensity immediately on the cessation of the stimulation. Thus there is no possibility of escaping the full effect of the brightness after-image on the stimulus color, as might happen in the central retina where a latent period obtains, if there were a very short exposure to the color.

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A NOTE ON THE SELECTIVENESS OF THE ACHROMATIC RESPONSE OF THE EYE TO WAVE-LENGTH AND ITS CHANGE WITH CHANGE OF INTENSITY OF LIGHT

BY C. E. FERREE AND G. RAND

Bryn Mawr College

In Dr. Troland's review of the article by us on this subject (PSYCHOL. BULL., 16, 121) errors of statement occur on two important points. (1) "Unfortunately the writers do not speak of the size of field employed, so that one can not feel certain that strictly foveal stimulation was secured." The sizes of the fields employed are given on pp. 283 and 284, and again on p. 304, of the article reviewed. (2) "Ferree and Rand have made careful measurements of visibility curves at a number of intensity levels and find that the form of the curve varies radically with intensity even for intensity levels similar to those utilized in previous elaborate investigations by others. . . . The changes in visibility for certain wave-lengths due to intensity amount to many hnudred per cent." The form of our curves did not vary *radically* with intensity at the levels which have been used in recent determinations of standard visibility curves, meant to be independent of intensity. The differences at these intensities were significant but not radical. The radical differences were for much lower intensities 5 meter-candles and under. The impression certainly should not be left that the differences amount to many hundred per cent. at the higher intensities. It is doubtful if the Purkinje shift can be estimated in per cent from our data in the sense referred to by Troland. What was given in our tables was a comparison of the photometric and radiometric evaluations of our stimuli at the different intensities. The deviation of these from exact correspondence of ratio as the intensity was changed ranged for the different parts of the spectrum used from 10 to 21 per cent. for a change of 75 to 50 meter-candles; from 14 to 48 per cent. for 75 to 25 meter-candles; and from 16 to 50 per cent. for 75 to 12.5 meter-candles.

We are not aware of published results of "elaborate investigations of others" contradictory to our own. The recent belief that the Purkinje shift ceases at 25 meter-candles or thereabouts seems to refer back to statements made by Ives and Nutting. Ives claimed that at "approximately 25 meter-candles" (300 meter-candles falling on a pupillary aperture of 1 sq. mm.) the achromatic response is practically, if not entirely free from Purkinje effects; and Nutting, that an illumination of 350 meter-candles falling on a pupillary aperture of 1.465 sq. mm. is safely outside the range of the Purkinje effects. Neither man cites results in support of his claim. Moreover the photometric determinations in the work in which these statements occur were made by the flicker method; ours were made by the equality of brightness method, or as the eye normally sees its brightnesses. There are good physiological reasons, also experimental data, for not expecting agreement by the two methods. Helmholtz and others of the earlier writers (Chodin, *Sammlung phys. Abhandl. v. Preyer*, 1877, 1, p. 33, ff., Brücke, *Sitzungsber. der Wiener Akad.*, Math.-Natur. Klasse, 1878, (3), p. 63; etc.) believed that the eye changes its selectiveness of response to wave-length of light at the higher as well as at the lower intensities. This conclusion is drawn from a statement made by them that beginning with a spectrum of fully saturated colors and increasing the intensity of light, all the colors tend towards white and in so doing change their luminosities at different rates.

The question with regard to the intensity at which the Purkinje shift ceases, if at all, should be carefully studied before still more effort is expended on determining visibility curves meant to be used at 25 meter-candles and over.

A METHOD OF STANDARDIZING THE COLOR VALUE OF THE DAYLIGHT ILLUMINATION OF AN OPTICS ROOM

By C. E. Ferree, G. Rand, and I. A. Haupt, Bryn Mawr College.

In a previous article (Psychol. Rev. 1912, XIX, pp. 364-373) we have given a method of standardizing the intensity of light in an optics room illuminated by daylight and have described provisions for keeping constant the intensity selected as standard. If still more exact conditions are wanted for conducting work on color sensitivity another variable, namely, the changing color of daylight, should perhaps be taken into account. It is the purpose of this paper to describe a method of standardizing the color value of the daylight illumination of a room and of correcting the changing values to the standard value in such optics rooms as we have in our laboratory.

We mean by standardizing here only a means of matching the daylight selected as desirable and of reproducing at any given time as a standard the color value which matches the daylight selected. Our plan does not include primarily a means of determining what is the most desirable color value of daylight to use, although that might well be made a valuable feature of the plan. To be of the greatest service in psychological optics the plan should be both reasonably simple of accomplishment and have a fair degree of precision. In devising a method we have endeavored to keep both of these requirements in mind. Obviously the first step to accomplish is to have a source of light the color value of which can be kept constant within acceptable limits. A well seasoned tungsten light operated by a constant current gives a light of sufficient constancy of composition to serve our purpose.[1] It has

[1] In reply to an inquiry about the constancy of color value of the light emitted by the tungsten filament operated at a constant voltage, also its constancy as compared with the light emitted by the carbon filament, we have the following from the Bureau of Standards. "With regard to the constancy of the color from lamps operated at a constant voltage, it can be said in general that almost any seasoned incandescent lamp will burn a considerable time without any appreciable change in the color of the light, unless the filament is operated at a temperature above the normal. In comparing carbon with tungsten filaments the relative constancy will depend on the conditions. If the two are set at voltages which will give the same color, the tungsten will change much more slowly than the carbon In fact a tungsten filament operated at the normal color of carbon lamps will usually

the advantage too that its changes of color with change of voltage are roughly similar in direction to those which occur in daylight. A second step is to have a means of changing the color value of the light to match the daylight selected as desirable and a comparison surface on which to make the match. The first of these purposes can be accomplished by means of thin gelatine filters of known spectrum transmission, properly selected and combined to give the color values needed; and the second by means of any photometer head which presents a sufficiently good field for the comparison. We have already described a simple and inexpensive photometer for daylight work which with the proper selection of filters can also be made to serve the present purpose very well. For a description of this photometer the reader is referred to this Journal, 1916, XXVII, pp. 335-340. When the proper filters are inserted on the side next to the standard lamp this photometer can be used to make both the photometric and colorimetric comparison with no change either in the apparatus or the adjustment of the lamp. With the instrument set for the color and intensity of light selected as standard it can be determined at a glance whether the illuminaton of the room fulfills the desired requirements with regard to both of these features.

We have stated that the method employed should have a satisfactory degree of precision and sensitivity. In order to get some estimate of the sensitivity of the method or what amounts of color change can be detected at different intensities of illumination, the following experiments were conducted. (1) The light from two well seasoned tungsten lamps of equal watt value (40-watt, type B Mazda) was brought to a color and brightness match at the photometer head. The change in voltage required to produce a just noticeable change in color tone was then determined. The work was conducted in a dark room and for convenience in getting the proper range of intensities the photometer head was removed from its place in the box photometer and mounted on an ordinary photometer bar. In making the determinations one lamp, A, was operated at 107 volts and set at the desired distance from the photometer head. The other lamp, B, was operated at such a voltage and set at such a distance from the head as was needed to give an exact color and brightness match. When

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burn thousands of hours with no appreciable change in color. Whether different lamps of the same kind give light of the same color depends on how closely the lamps are kept uniform in manufacture. As furnished on the market at present different tungsten lamps of the same size will be found to be more nearly alike than carbon lamps."

the match was obtained the voltage of lamp A was lowered until a just noticeable difference in color tone could be detected at the screen. A measure was thus had of the amount of color change that could be detected by the instrument in terms of the amount that is produced by a given variation of the voltage of a tungsten lamp the specification and the conditions of operation of which are known. When the voltage of lamp A was lowered the intensity as well as the color value of the light at the photometer head was changed. This required a resetting of the lamp B to bring the two photometric fields to equal brightness. However, as a check on the judgment of just noticeable difference in color tone each observation was made under more than one brightness relation between the two photometric fields. The judgment was not difficult to make. Its precision in fact compares very favorably with that of the photometric judgment. The determination was made with the lamps at different distances from the photometer head,—14, 20, 30, 40 and 50 cm. to give the differences in intensity at which it was desired to make the determinations of colorimetric sensitivity. For the sake of a comparison of the colorimetric sensitivity of the photometer heads more commonly used, the determinations were repeated with Lummer-Brodhun heads of the contrast and disappearance types. The results of these determinations are given in Table I.

TABLE I*

A Comparison of the Sensitivity of Different Photometer Heads To Change in Color of Light of Tungsten Lamp (Madza Type B) Operated at 107 Volts

Distance of Lamp From Photometer Head (cm.)	Voltage Change of Lamp to Give Just Noticeable Change of Color Tone		
	Lummer Brodhun Head Contrast Type	Lummer Brodhun Head Disappearance Type	Bunsen Head
14	0.25	0.5	1.0
20	0.50	1.0	1.5
30	0.75	1.5	2.5
40	1.00	3.0	3.0
50	1.25	3.5	3.0

*The results of this and the following tables are for Observer R. The main points were verified by a check observer, H.

(2) In the second series of experiments a comparison was made of the sensitivity to change of color tone with the three photometer heads, the Bunsen and the two types of Lummer-Brodhun, when the photometric surfaces were illuminated by the tungsten lamps, natural color, and when they were illuminated by the light from these lamps filtered through gelatines so selected as to match the daylight in one of our optics rooms at 11 A. M. on a clear day. The intensity of light at the photometer head was made the same for both kinds of illumination. The comparison was made at three intensities of illumination, corresponding to those given by the tungsten lamps in the preceding set of experiments when placed at 30, 40 and 50 cm. from the photometer head. The comparison was not made for the other intensities because they could not be obtained on our photometer bar on account of the reduction in intensity produced by passing the light through the daylight filters. That is, the lamps could not be brought nearer to the photometer head than 14 cm. and to match the tungsten lamp at 30 cm. from the head, for example, the lamp in front of which the filter was placed had to be set at a distance of 14.3 cm. The results of this comparison are given in Table II.

TABLE II

A COMPARISON OF THE SENSITIVITY OF DIFFERENT PHOTOMETER HEADS TO CHANGE IN COLOR OF LIGHT OF TUNGSTEN LAMP (MADZA TYPE B) OPERATED AT 107 VOLTS AND OF THIS LIGHT FILTERED TO MATCH DAYLIGHT

Distance of Lamp From Photometer Head Giving Equal Illumination for Each Intensity for		Voltage Change of Lamp to Give Just Noticeable Change of Color Tone					
		Type B Mazda Lamp			Type B Mazda Lamp With Daylight Filter		
Type B Mazda Lamp (cm.)	Type B Mazda Lamp With Daylight Filter (cm.)	Lummer Brodhun Head Contrast Type	Lummer Brodhun Head Disappearance Type	Bunsen Head	Lummer Brodhun Head Contrast Type	Lummer Brodhun Head Disappearance Type	Bunsen Head
30	13.5	0.75	1.5	2.5	0.25	0.50	0.75
40	18.8	1.00	3.0	3.0	0.25	0.50	1.00
50	25.2	1.25	3.5	3.0	0.25	0.75	1.50

(3) A somewhat limited comparison was made of the sensitivity of the Bunsen head to change in color tone when the photometric surfaces were neutral and when they were colored. This was done because the color of some pigments is known to be very sensitive to changes in color value of the

light falling upon them. For the purpose of making this comparison a number of such standard pigments as are commonly found in psychological laboratories were substituted for the white screen of the Bunsen head. Two cases were made of this investigation. (a) Six colored screens were used, selected from the Hering series of papers: the dark red, the orange, the yellow, the yellowish green, the blue-green and the violet; and three from the Milton-Bradley series: the red-violet, the red-violet, tint No. 1 and the orange-red, tint No. 1. The light from the 40-watt lamp was in each case passed through the daylight filter referred to above. The brightness of the photometric surfaces was kept constant in all cases at a value equal to that of the white screen illuminated by the filtered light of the tungsten lamp at a distance of 74 cm. This was the highest brightness that could be obtained with this lamp for the colored screen having the lowest coefficient of reflection. This intensity of illumination was selected in order that the colorimetric comparison should be made in all cases for the same brightness of surfaces compared. The results of this comparison are given in Table III. (b) Since in the preceding

TABLE III

A Comparison of the Colorimetric Sensitivity of the Bunsen Photometer Head When Provided With White and Colored Fields—This Comparison was Made With the Intensities of Light Adjusted to Give in All Cases the Same Brightness of Photometer Fields, Namely, the Brightness of the Blue Pigment (Pigment With Lowest Coefficient of Reflection) Illuminated With the Highest Intensity That Could Be Obtained With the Filtered Light of the Mazda Type B Lamp Operated at 107 Volts

Photometer Field	Distance of lamp (cm.) from photometer head giving brightness of colored fields equal to that of white field illuminated by this lamp with daylight filter at 74 cm.	Voltage change of lamp to give just noticeable change of color tone.
Yellowish-green	43.0	1.0
Violet	15.1	2.0
Red-violet	22.6	3.0
Orange-red, tint No. 1	40.0	3.0
Red-violet, tint No. 1	33.5	4.0
Yellow	50.8	4.0
Orange	38.0	5.0
Dark red	31.5	6.0
Blue	13.8	6.0
Blue-green	27.3	8.0
White	74.0	4.0

experiments the pigments of the higher reflection coefficients had to be used at lower illuminations than the other pigments in order to fulfill the conditions that the colorimetric comparison should be made in all cases on surfaces of equal brightness, it was decided to make a comparison of the most favorable of these colors with the neutral screen at illuminations approximately equal to that used for the color of lowest reflection coefficient in the former experiments. This, it will be remembered, was the highest that could be obtained with the filtered light of the 40-watt lamp. For this purpose the yellowish green, the yellow and orange-red, tint No. 1, screens were used. The results of this comparison are given in Table IV. These results, it scarcely need be pointed out, have a

TABLE IV

A Comparison of the Colorimetric Sensitivity of the Bunsen Photometer Head When Provided With White and the More Sensitive Colored Fields Used in Table III, at Intensities of Illumination Equal Approximately to the Highest That Could be Obtained With the Filtered Light of the Type B Madza Lamp Operated at 107 Volts

Photometer Field	Distance of lamp (cm.) from photometer head giving equal brightness of white and colored fields for Mazda type B lamp with daylight filter	Voltage change of lamp to give just noticeable change of color tone
Yellowish-green	16.5	0.25
White	26.5	1.50
Yellow	13.5	1.50
White	20.0	1.0
Orange-red, tint No. 1	15	1.50
White	22	1.25
Violet	15.1	2.0
White	74	4.0

much more direct bearing on the problem of selecting screens for our standardizing instrument than those of the former comparison. That is, in the selection of screens for such instrument we are concerned with relative sensitivities at equal illuminations, not equal brightnesses, of screen. Obviously in the final selection of screens for any particular instrument that screen should be chosen which shows the greatest sensitivity for the range of illuminations possible for the instrument or for the range that is likely to be used.

An inspection of the results in Tables I-IV shows the following points.

(1) As might be expected smaller color changes could be detected at the higher than at the lower intensities of illumination. That is, at the higher intensities the color of the light was less saturated (the inhibitive action of the achromatic on the chromatic component of the retinal excitation) therefore a smaller change was needed to be just noticeable.

(2) The colorimetric sensitivity of the photometer heads employed is in the following order from greatest to least,—the Lummer-Brodhun, contrast type; the Lummer-Brodhun, disappearance type; the Bunsen. As bearing on the type of field that gives high colorimetric sensitivity such comparisons are of importance to colorimetry by the monochromatic method.

(3) Smaller changes of voltage were required to produce a noticeable change in the color of the light filtered to match daylight than in the color of the unfiltered light of the Mazda type B lamp.

(4) Of all the colored screens employed the yellowish-green, the violet, the yellow and the orange-red, tint No. 1, showed greater sensitivity to changes of color of light of the type produced in these experiments (changes similar to those which occur in daylight) than the white screen when the comparison was made at equal brightness of screen. When, however the comparison was made at illuminations approximately equal to the highest illumination that could be obtained with the filtered light of the 40-watt lamp only the green showed a greater colorimetric sensitivity than the neutral screen. The green screen seemed to be peculiarly sensitive to the changes which are produced by adding the longer wave-lengths to daylight. That is, the adding of the red wave-lengths appeared to decrease the saturation of the green and the adding of the yellow wave-lengths, to increase the yellow component already present. At the highest intensity of illumination used a change of only 0.25 volt was needed to cause a noticeable change in the color of the screen. Indeed at this intensity of illumination the colorimetric sensitivity of the Bunsen head was so much improved by the substitution of the green screen as to equal that of the more sensitive of the two Lummer-Brodhun heads with the white screen.

As we have already indicated the work of standardizing

for color value and intensity may be done at the same time. It may be accomplished as follows: A daylight is selected of the color value and intensity desired. On the side of the photometer head next to the standard lamp gelatine filters are inserted so chosen that when the light from this lamp run at a given voltage and set at the position on the bar needed to give the intensity match, is filtered through them, the photometric surfaces illuminated by this light match in color value the surface illuminated by the daylight. To reproduce this standard at any future time all that is needed is to reset the lamp in the same position on the bar and to reproduce the voltage. With the photometer set up at the point of work in the room or as near to it as possible, the process of checking up the illumination both as to color value and intensity becomes very simple. A glance at the photometric field is sufficient to give the desired information. Since it is not so easy to arrange for the correction of daylight to the color value chosen as standard as it is to correct the intensity, feasibility may dictate that the work be done within a certain range of variation of color value. The apparatus recommended may be used to standardize this range as follows: If the daylight chosen as desirable be that of skylight near the middle of a clear day the changes that are apt to occur during the course of the day or from day to day may be approximated roughly by lowering the voltage of the standard lamp or by lowering the voltage supplemented by the addition of one or more of the thin gelatine filters properly selected. When this is done and the lamp is reset to compensate for the change of intensity produced, a range of variation of color value is fixed within which the daylight illumination must fall or be rejected for the particular work in hand. In such a case the photometer is set so that the standard surface in the photometer head is illuminated with the light chosen as the limit towards which the color value may vary and still be accepted for the work in hand. It is very easy then at any particular time to judge whether the dominant color of the daylight incident upon the receiving surface of the photometer falls within the limiting value.

Obviously a means of correcting the changing daylight to the color value chosen as desirable would be an advantageous supplement to the work of standardizing. The method we purpose for use for this is as follows: At a distance above the diffusion sash of ground glass installed beneath the sky-

light in our optics rooms, sufficient to give a good spread of light, will be installed opaque pendant reflectors of the distributing type. These reflectors will be supplied with filters which transmit an excess of the short wave-lengths. They will be installed on separate circuits, one or more to the circuit, so that a variable proportion of the artificial light may be used as is needed. Further to vary both the composition and the amount of artificial light used, wall rheostats will be included in as many of the circuits as is found to be advisable. Quite a wide range of composition and intensity of light can be obtained also by the use of lamps of different types and wattages. The artificial units may be installed well out of the road and the desired direction and throw of light be obtained by the shape of the reflector and the angle at which it is installed. Further the amounts of daylight used in getting the desired composition may be controlled by a system of curtains placed under the skylight above the diffusion sash and the artificial units. The elaborate system of curtains which is already installed beneath the diffusion sash in our rooms will serve as they do now for fine gradations of intensity of light and may prove useful to some extent perhaps for the control of the composition.

An alternative to a flexible system of correction of actual daylight for both composition and intensity is the utilization of some one of the artificial daylights which are now on the market. Of the unfiltered sources the carbon dioxide tube gives perhaps by common agreement the closest approximation to skylight. Its cost, however, is prohibitive for the greater number of laboratories. The same thing might well be said of the best of the filter units. The ones most familiar to us all and the most available from the standpoint of cost are the blue bulb lamps. With regard to these lamps, however, only a rough approximation to daylight is claimed. We have thought that it may be of interest to show here a spectrophotometric comparison of one of them, the type C-2 Mazda lamp, and of some of the closer approximations to daylight, with the black body at 5000 degrees absolute which is sometimes taken as the standard of average daylight. (See Fig. I.) For the comparative curves given in this figure we are indebted to the Electrical Testing Laboratories, 80th street and East End avenue, New York City. The comparison here, it will be remembered, is photometric, not colorimetric.

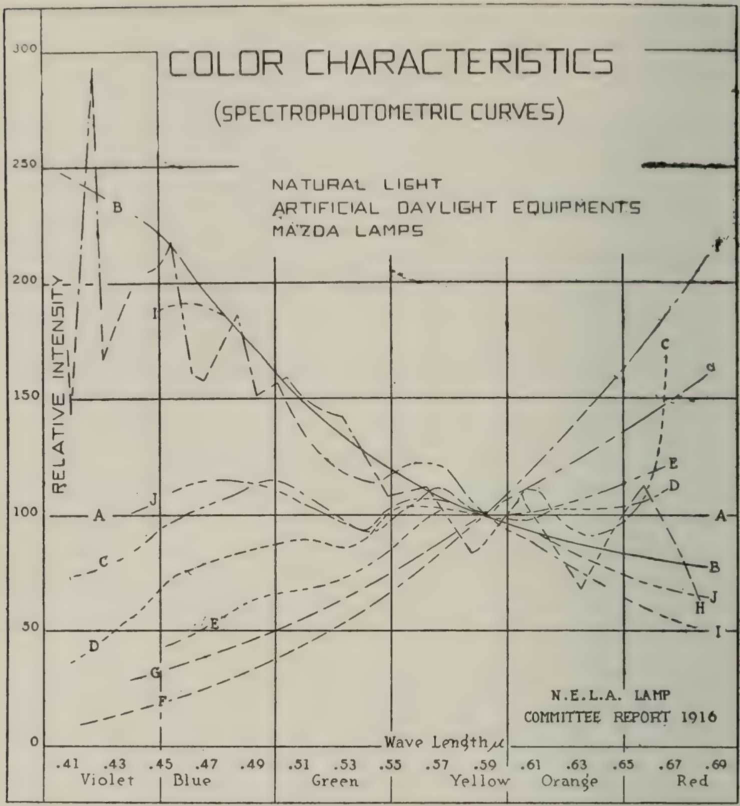

Fig. I

A—Black body at 5000 degrees absolute ("Average Daylight")
B—Blue sky (Ives) I. E. S. Transactions, 1910, p. 208.
C—Daylight glass with Mazda C lamp (Brady) I. E. S. Transactions, 1914, p. 952.
D—Bluish glass with Mazda C lamp (Sharp) I. E. S. Transactions, 1915, p. 220.
E—Mazda C_2 lamp.
F—Mazda B lamp (7.9 lumens per watt).
G—Mazda C lamp (20 lumens per watt).
H—Moore tube (Paper read before I. E. S. November 11, 1915).
I—Trutint glass, (Luckiesh) I. E. S. Transactions, 1914, p. 839.
J—Trutint glass, (Luckiesh) I. E. S. Transactions, 1914, p. 839.

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AN APPARATUS FOR DETERMINING ACUITY AT LOW ILLUMINATIONS, FOR TESTING THE LIGHT AND COLOR SENSE AND FOR DETECTING SMALL ERRORS IN REFRACTION AND IN THEIR CORRECTION

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This apparatus was devised in response to a request by the Eye Division of the U. S. Naval Hospital for a means of making a quick and accurate test of acuity at low illumination. Experience has shown, roughly speaking, that only 25–30 per cent. of the men on the battleships have a sufficiently keen acuity at low illuminations to qualify for all branches of the lookout and signal service work. The apparatus provides for a wide range of illumination in just noticeably different steps (beginning at 0.07 meter-candle or lower), with no change in the color value of the light and with a specification at each step of the intensity of light falling on the test-object.

Among the requirements for an apparatus for determining acuity at low illuminations or the effect of change of illumination, the following points may be mentioned. (1) A means of changing the illumination by small amounts over a wide range, beginning at or below the threshold for the test-object employed, without changing the color value of the light. If in making this change the color value of the light is altered it is obvious that another factor affecting the results is introduced. (2) A means of keeping constant for an indefinite length of time any desired intensity of illumination and of reproducing this intensity at will. Also the test-object must be uniformly illuminated. (3) A means of specifying accurately at any point in the scale the intensity of light falling on the test-object. And (4) it is desirable that the apparatus employed for controlling the illumination can be used with the test-objects already accepted in clinic practice.

The most difficult problem one has to face in constructing an apparatus for determining the min'mum amount of light that permits of the discrimination of a given test-object, more particular'y if that object consists of a line of test letters, is to secure a uniform illumination of the line. This problem is relatively unimportant at the illuminations ordinarily used in acuity testing, because at these illuminations acuity changes so slowly with chan e of intensity of light that the differences which may occur throughout the line of test letters do not ordinarily produce a detectable effect on the results of the test. However, if no more care is exercised at the threshold to secure uniformity of illumination than is ordinarily used at the higher illuminations, no single intensity at the source will serve for the discrimination of all of the letters of the line. We were able satisfactorily to meet this difficulty in only one way, namely, by selecting an aperture sufficiently small to permit of its uniform illumination and projecting a magnified image of this aperture on the test card. That is, an aperture was selected of such a size and shape that when magnified fivefold it gave a band of light which just blocked off one line of the test letters. It is obvious that this aperture could be made of different sizes and shapes, depending upon what is wanted in the projected image. For example, two or three lines of test letters could be blocked off if desired, or the whole card or any part of it could be illuminated, etc. There is no reason, moreover, why the aperture could not be made adjustable in size to suit the needs and preferences of the individual operator. In one model of the apparatus these apertures were cut in a series of slides which could be inserted in the projection tube just outside the lamp house in grooves in a light-tight boxing. A convenient means was thus provided for changing the aperture, if desired, during a series of tests without having to open the lamp house. The source of light is a well-seasoned Mazda C lamp of the round bulb or stereopticon type of 100, 250 or 500 watts, depending upon the range of illumination that is desired. This lamp is installed vertically in the roof of the lamp house at such a height that its filament is well above the aperture which is

to be illuminated. In order to secure a uniform and diffuse illumination of the aperture the lamp house is lined with opal glass ground on one side. The aperture, 6 x 1 cm., is cut at the center of the cap covering the inner end of the projection tube. Further to aid in the even illumination of the aperture, it is covered with a slide of ground glass. To prevent the overheating of the lamp house, a rather elaborate ventilating system is provided consisting of a light-tight ventilating hood at the top and a series of holes on two sides at the bottom of the housing, furnished with light-tight shields. The changes in the intensity of light are produced by means of an iris diaphragm. When such a diaphragm is placed either at the front or back surface of the focussing lens, changes in the flux of light can be produced without any alteration in the size or the shape of the image produced by the lens, just as happens, for example, in the action of the iris of the eye. At a suitable point in the circumference of the diaphragm is fastened a pointer which, as the diaphragm is opened and closed, moves over a translucent millimeter scale. This scale is mounted over a slot in the projection tube and receives its illumination from the light inside of the tube. The inside of the tube is painted a mat black. At the further end of the projection tube, 18.1 cm. from the illuminated aperture, in a brass ring and collar is mounted the focussing lens. This lens is 7.5 cm. in diameter and has a focal length of 14.8 cm. A different strength of lens could have been used and different relative distances of aperture and test card from the lens. With appropriate variations in these factors the distance of the lantern from the test card and the amount of magnification of the projected image may be varied. Any increase of magnification results of course in a decrease in the brightness of the image, hence an increase in the scale of brightness of image with no change in its size could have been obtained by increasing the size of the aperture and decreasing correspondingly the amount of magnification. In the construction of the present apparatus a 14.8 cm. focal length lens was used because it could be obtained the most readily on the market of the diameter needed. On the plat-

form supporting the lamp house are mounted a small Weston ammeter and a small rheostat to guard against fluctuations in the current and consequent fluctuations in light intensities. In order that any line of the chart may be illuminated at will, the lamp house is mounted on the end of a rod which is raised and lowered by means of a rack and pinion. The test card is mounted at a distance of 81 cm. from the focussing lens. A photograph of the apparatus is shown in Fig. 1.

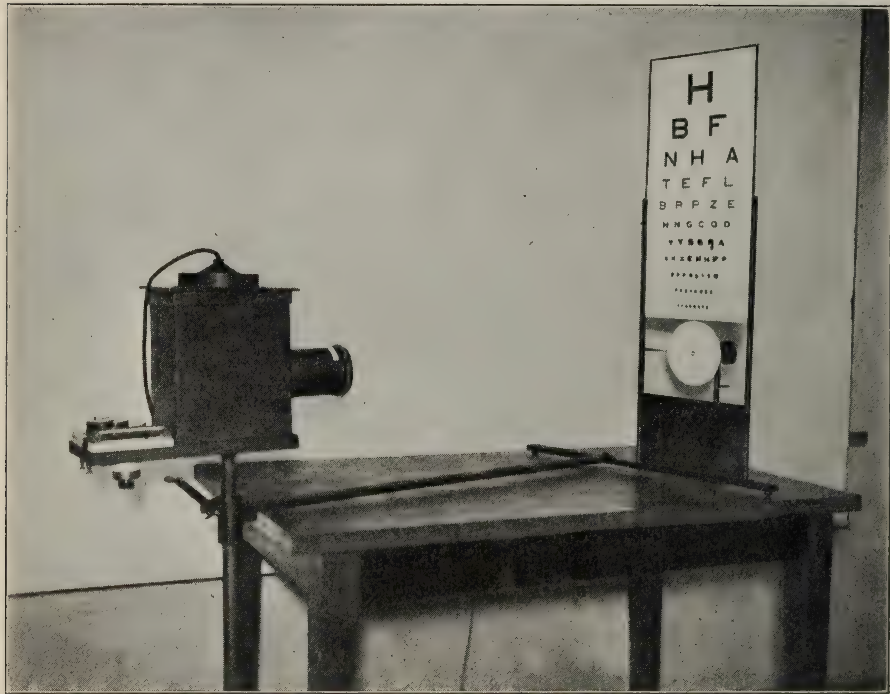

Fig. 1.

In order that the intensity of light used at any time may be known, a calibration chart is provided in which are given the readings on the millimeter scale and the equivalent meter-candle values at the test card. This calibration was accomplished as follows: The lamp house was removed and mounted on a photometer bar at a distance from the photometer head equal to its original distance from the test card. The scale

was then gone over point by point and the meter-candle value of the light at the photometer head was measured. The calibration chart is shown in Fig. 2 *a*. In Fig. 2 *b* is shown the calibration curve in which the divisions of the millimeter scale are plotted against meter-candles at the test card. These values are corrected to conform at the center of the card to the cosine law.

Diaphragm Setting	Meter-candles	Diaphragm Setting	Meter-candles
82.5	9.19	46.0	2.46
82.0	9.04	44.0	2.23
80.0	8.54	42.0	2.02
78.0	8.06	40.0	1.81
76.0	7.58	38.0	1.61
74.0	7.12	36.0	1.43
72.0	6.67	34.0	1.27
70.0	6.23	32.0	1.12
68.0	5.81	30.0	0.97
66.0	5.43	28.0	0.82
64.0	5.06	26.0	0.69
62.0	4.71	24.0	0.58
60.0	4.36	22.0	0.48
58.0	4.02	20.0	0.38
56.0	3.72	18.0	0.28
54.0	3.45	16.0	0.21
52.0	3.18	14.0	0.16
50.0	2.93	12.0	0.11
48.0	2.69	10.0	0.07

FIG. 2*a*. Calibration Table.

For our own use in the laboratory we have preferred to substitute for the Snellen chart a single test character, the broken circle (the international test object), which can be turned in different directions and the judgment of its direction rather than the recognition of the character be required of the observer as a test of discrimination. Our reasons for this preference are as follows: (1) A test letter may be recognized when it is not seen at all clearly. Recognition is too dependent on extraocular functions to be used with precision as a measure of ocular capacity. (2) The different letters of the Snellen chart set an unequal task for the resolving power of the eye. (3) An objective check is had on the judgment. This is especially helpful in case of children, and the unintelligent, untrained and subjective type of adult. (4) By the use of the same test character, turned in different direc-

tions at will, all possibility of learning the test series is eliminated. Also the test-object becomes much more valuable for the detection of astigmatisms. And (5) at low

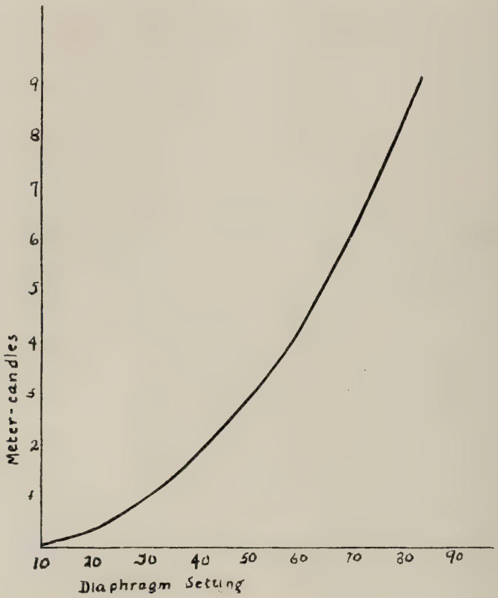

FIG. 2*b*. Calibration Chart.

illuminations the eye fatigues very rapidly. Thus if the task is the reading of the whole line of letters the results obtained measure not only acuity, but the power to sustain acuity which may or may not be compatible with the purpose of the test.

As stated in the introduction, the apparatus was designed to meet a specific testing need of the Navy. However, it has in addition the following laboratory and clinic uses. (1) Photopic acuity may be tested under the conditions of a constant and uniform illumination of known intensity. In case the test-object is a line or chart of letters, provision is made that each letter receives, within sensible limits, equal amounts of light. (2) Scotopic or twilight vision may be tested—also the amount and rate of scotopic adaptation. A precise and feasible means is thus afforded for testing the light sense insofar as it affects the power to see clearly. (3)

If the image of the aperture is projected on a blank white surface of good reflecting power, more particularly if its size and shape are changed to that of a square or circle of dimensions favorable for making a sensitive judgment, the apparatus can be used with an equal degree of precision and convenience for testing the light sense directly in terms of the amount of light required to arouse just noticeable sensation. That is, the threshold of sensation can be determined in terms of meter-candles of light falling on the test surface; or, knowing the coefficient of reflection of this surface and the breadth of pupil, in terms of the amount of light entering the eye. The testing of the light sense will probably always remain foundation work in the clinic routine. The testing of scotopic acuity, for example, is not sufficiently differential in all cases between refraction defects and the hemeralopias and other retinal deficiencies to serve as a satisfactory substitute. There is, at present, we are told on very good authority, no satisfactory instrument for testing the light sense available to the ophthalmologist. And (4) by making it possible to determine with great exactness the minimum of illumination at which the test-object can just be discriminated, the apparatus provides a very sensitive means for detecting small errors in refraction and in their correction, as will be demonstrated in a later paper.

Sensitivity for detecting small errors in refraction and in their correction could also be added to the acuity test by using a test-object, small changes in the size of which could be made. However, no means has as yet been provided for making small changes in the size of any acuity object sufficiently complicated in form to test simultaneously the resolving power of the eye in any great number of meridians which is, we believe, a very important feature in determining the exact location of an astigmatism or the exact amount and placement of its correction, more particularly when a cycloplegic is not used.

We consider this an important feature in testing for an astigmatism because of our belief that the astigmatic eye in the attempt to compensate for its defect has in many cases

at least acquired unusual powers and habits of accommodation. Our belief in this is based on three sets of observations. (1) In the use of the astigmatic charts without a cycloplegic in cases of low astigmatism, one is frequently annoyed by the astigmatic indication shifting from one meridian to another. (2) We have found observers who could voluntarily, in some cases requiring considerable practice, shift the meridian showing the astigmatic indication. And (3) in our test of astigmatism based on the relative speed of discrimination in the different meridians, *American Journal of Ophthalmology*, 1918, I., pp. 3–16, the speed of discrimination for the least favorable meridian can be increased by practice almost to equal that in the most favorable meridian with an equal amount of practice. This result is so noticeable that in order to make the test sensitive we were compelled to eliminate as much as possible the opportunity for the practice effect. This was done in two ways. (1) The series was always begun below rather than above the minimum time of exposure required just to detect the direction in which the test-object was turned. And (2) meridians were inserted in the series clearly outside of the region of maximum astigmatic effect in order to break up any progressive tendency to accommodate especially for the meridian showing the poorer resolving power. The fact that the eye can with long exposures discriminate a fineness of detail in its unfavorable meridian which it is utterly unable to master with short exposures and that this excess lag can be overcome in a considerable measure by practice seems to indicate that it has the power through its active accommodation to overcome in part the effect of meridianal inequalities in resolving power, at least when a test-object taxing the resolving power in only one meridian is turned successively into different meridians. In any event it seems only the part of sound procedure in testing without a cycloplegic to guard against the possibility of selective meridianal accommodation by the use of a test-object which taxes the resolving power of the eye in as many meridians as possible.

But even if a test-object complicated in form and minutely

adjustable in size were available, a device for determining the minimum illumination at which the test-object subtending the standard visual angle can just be discriminated would afford a still more sensitive means for the detection of low astigmatisms and small errors in the amount and placement of their correction. This follows rather obviously from the fact that for all but very low intensities acuity changes slowly with change of illumination. That is, for all but very low intensities small differences in acuity correspond, comparatively speaking, to large changes in illumination. Used as we have recommended, the illumination scale becomes in effect an amplified indicating scale by means of which the relatively slight differences in acuity, represented by the proper correction of an error in refraction and small deviations therefrom, may be detected with comparative ease and certainty. It is not infrequent perhaps to find that in cases of low astigmatism, with the full illumination of a test-object presenting no smaller gradations in visual angle than are found in the Snellen chart, the observer is able to detect no difference in the ease or clearness of discrimination of the test character through a range of from 20–40 degrees in the placement of the correction. This difficulty is especially annoying in the case of children and the unintelligent, untrained and subjective type of adult. In such cases the apparatus shown here is especially helpful. With it a minimum is left to the comparative and observational powers of the subject. All that he is required to do is to indicate the direction in which the test-object points, the most favorable amount and placement of the correction being determined by the minimum amount of illumination at which he is able correctly to give this indication. The apparatus possesses ample sensitivity, as our results will show, for the detection of an error of 5 degrees and less in the placement of the correction of a low astigmatism or of 0.12 diopter and less in the amount of the correction.

In a table to be given in a later paper it will be shown, for example, that an error of 5 degrees in the placement of the correction of an astigmatism produced by a 0.25 diopter cylinder

required as an average for five eyes 66.5 per cent. more light for the discrimination of the test-object than the correct placement; in case of an astigmatism produced by a 0.75 diopter cylinder it required 107.2 per cent. more light than the correct placement. The large number of scale divisions between the settings of the light control for the correct and incorrect placements of the cylinder will be shown also in these results. In case of the 5-degree displacement of the correction of 0.25 diopter astigmatism this difference averaged 9.6 for the five eyes. Since the apparatus can readily be set to half divisions, 19 settings of the light control could have been made with precision between the values needed for the true correction and the 5-degree displacement. This shows that the sensitivity of the apparatus far exceeds the present possibilities of the precise manipulation of the correcting cylinders.

In case of an error of 0.12 diopter in the amount of the correction, 54.6 per cent. more light was required for the least favorable meridian; and in case of an error of 0.25 diopter, 108.9 per cent.

The relation of the illumination scale to the detection of small errors in refraction and in their correction may be stated briefly as follows: Insofar as the test-object is concerned, clearness of seeing depends upon the value of the visual angle subtended and the intensity of the illumination. It follows from this that either the illumination scale or the visual angle scale may be used for the detection of errors in refraction, *i.e.*, in the diagnostic procedure either the illumination may be held constant and the visual angle varied, or the converse. Since the visual angle scale sustains by convention a 1 : 1 relation to acuity while acuity changes slowly with change of illumination for all but very low intensities, the illumination scale possesses the greater sensitivity for the detection of small errors in refraction—also the greater ease and feasibility of contrivance and manipulation. Used in this way the illumination scale becomes in effect an amplifying scale—somewhat analogous to the use of the tangent scale in detecting small deflections in the magnet system of a

galvanometer—and has an advantage in sensitivity in proportion to the amplification. In clinic practice it has been shown to be of particular value in determining the exact amount and placement of the correction of astigmatisms. That is, if the eye has equal resolving power in all meridians, the amount of light required just to discriminate the test-object in all meridians will be the same; if the resolving power is not equal, the amount of light required will be different in the different meridians and different by an amount proportional to the amplification represented by the illumination scale. A more detailed discussion of a feasible and convenient means of using the illumination scale in office and clinic practice will be given later.

Attachment for Testing the Light and Color Sense

A consideration of the foundation principles of the acuity apparatus reveals at a glance that they lend themselves readily to light and color sense testing for clinic purposes. In order to convert the apparatus in the form described in this paper into a light sense tester three features are needed: (*a*) the choice of an aperture such that when magnified five-fold a stimulus is obtained of a size and shape suitable for a sensitive judgment of the threshold of sensation; (*b*) the provision of a suitable surface on which to project the magnified image of the aperture; and (*c*) a means of reducing the intensity of light from the acuity threshold to the light sense threshold, *i.e.*, from the amount needed just to discriminate the standard acuity object to the amount needed just to arouse the light sensation. The iris diaphragm used in the present form of apparatus, range of pupil 5–65 mm., does not provide for this range of intensity without changing the source of light. It is obvious that an attachment for the further reduction of the light which does not interfere in any way with the use of the apparatus for the acuity work, would afford a more convenient means of securing the lower intensities than the changing of the source of light. Provision has been made for this in two ways: (*a*) by neutral absorption screens or filters; and (*b*) by a Nicols prism (polarizer and

analyzer). The attachment is made so that it will hold either of these reducing agencies, leaving the operator an option as to which shall be used. The filter holder is made from three grooved metal strips, 8 cm. long and of appropriate width and thickness, built into a three sided rectangular figure open at the top. It is fastened to a narrow collar which slips over the end of the projection tube of the acuity apparatus and is held in place by a set screw. The holder is provided with three grooves into which one, two or three filters 8 x 8 cm. may be inserted as desired, or the metal plate which holds the Nicols prism. The Nicols prism is mounted in telescoping tubes in the customary manner for reducing light intensities, one tube containing the polarizer and the other the analyzer. At the end of the tube containing the analyzer is a large milled head by means of which very small angles of rotation may be made. The angle of rotation is read by means of a graduated dial, 6 inches in diameter, and an indicator with a Vernier scale, attached respectively to the tubes containing the polarizer and the analyzer on either side of their junction. The tube containing the polarizer is firmly mounted in a brass plate, 8 x 9 cm., with its axis coincident with the normal to the plate at its center. When the Nicols is to be used instead of the filters, this plate is inserted in one of the grooves of the filter holder. So inserted its axis is in the principal axis of the projection lens of the acuity lantern and the inner end of the polarizer is in contact with the outer surface of the projection lens. When the filters are employed to reduce the light they are inserted in the holder to give the large initial cut down and the further graded reduction is made by the iris diaphragm of the acuity lantern. When the Nicols is employed, the iris diaphragm is set at its minimum aperture, 5 mm., and the further reduction is made by the Nicols and read from its scale.

The testing of the color sense is provided for by inserting color filters in the beam of light. These filters may be inserted at the illuminated aperture; in the filter holder in front of the iris and lens; or, with a slightly different con-

struction of projection tube, back of the lens as near to the iris as possible. The simplest of these possibilities, from the standpoint of the construction and operation of the apparatus, is to insert the filter in the holder immediately in front of the lens and cut down the light intensity by means of the iris diaphragm. If it should be desired or considered technically more correct, however, to produce the changes in intensity after the light has been passed through the filter, this result can be accomplished either by inserting the filter at the illuminated aperture or anywhere in the projection tube back of the iris, or by placing it in the holder in front of the lens, with the iris held constant, and changing the intensity by means of the Nicols prism.

Color sense apparatus for clinic purposes seems at present, so far as the central field is concerned, to be limited to the testing of such gross deficiencies as are classed as color blindness. They are of little use for detecting the smaller changes which mark the advance and recession of many pathological conditions. The present apparatus is designed for detecting and measuring the degree of deficiency in terms of the amount of light of a given range of wave-lengths which is required just to arouse the color sensation.

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THE USE OF THE ILLUMINATION SCALE FOR THE DETECTION OF SMALL ERRORS IN REFRACTION AND IN THEIR CORRECTION

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There are doubtless many ways in which sensitivity can be added to the acuity test for the detection of small errors in refraction and in their correction. In connection with the problems which we have undertaken during the past eight years involving modifications and refinements in functional testing, three principles have come to light which can be used very effectively to this end. That is, the eye which suffers from an insufficient resolving power shows the following functional defects. (1) An undue lag or slowness of discrimination and of making the adjustments needed for clear seeing. (2) A marked loss in power to sustain the adjustments needed for clear seeing. And (3) an increase in the amount of light required just to discriminate details in the standard acuity object. The devising of test methods based on the first two of these principles has been treated of in former papers. The third alone will be considered here.

The relation of the illumination scale to the detection of small errors in refraction and in their correction may be stated briefly as follows. Insofar as the test-object is concerned, clearness of seeing depends upon the value of the visual angle subtended and the intensity of the illumination. It follows from this that either the illumination scale or the visual angle scale may be used for the detection of errors in refraction, *i.e.*, in the diagnostic procedure either the illumina-

tion may be held constant and the visual angle varied, or the converse. Since the visual angle scale sustains by convention a 1 : 1 relation to acuity while acuity changes slowly with change of illumination for all but very low illuminations, the illumination scale possesses the greater sensitivity for the detection of small errors in refraction—also the greater feasibility of contrivance and manipulation. Used in this way the illumination scale becomes in effect an amplifying scale—somewhat analogous to the use of the tangent scale in detecting small deflections in the magnet system of a galvanometer—and has an advantage in sensitivity in proportion to the amplification. In clinic practice it has been shown to be of particular value in determining the exact amount and placement of the correction of astigmatisms. That is, if the eye has equal resolving power in all meridians, the amount of light required just to discriminate the test-object in all meridians will be the same; if the resolving power is not equal, the amount of light required will be different in the different meridians and different in proportion to the amplification represented by the illumination scale. This gain in sensitivity over the clinic methods is needed in particular to determine the exact amount of the correction in case of high astigmatisms and both the amount and exact placement of the correction in case of low astigmatisms. The checking up of a number of cases shows that the corrections by the clinic methods may be and frequently are off from 0.12–0.25 diopter in the strength of the cylinder and, in case of low astigmatisms, from 5–20 degrees in the placement of the cylinder axis. While errors of this magnitude may or may not be troublesome in the ordinary uses of the eye—sometimes they are very troublesome indeed and, perhaps always tend in time to increase the amount of the defect—they do constitute a much more serious handicap, perhaps an actual disqualification, for work or vocations requiring special ocular proficiencies, *e.g.*, keen acuity, particularly keen acuity at low illuminations; the power to sustain acuity; speed in the use of the eye, especially speed of discrimination and of making the adjustments needed for clear seeing; etc. Moreover, it is safe to say that a considerably

greater amount of light is required as a comfortable and efficient working minimum by the poorly than by the well corrected eye. Indeed our experience with the tricornered relation of intensity of light, resolving power and retinal sensitivity to acuity has impressed us with the relative importance of resolving power in explaining the difference in the amount of light that is required by different people as a working minimum.

The relation of the intensity of illumination to acuity may be illustrated by the curve shown in Fig. 1. This curve represents the average results for four observers, tested by Koenig.[1] In this curve acuity is plotted along the ordinate and intensity of illumination along the abscissa. It will be noted, for example, that a change of from 1 to 9 meter-candles, an increase of 800 per cent. in the intensity of illumination, produced an increase of only 74 per cent. in acuity; and a change of 9 to 100 meter-candles, an increase of 1011 per cent. in illumination, produced an increase of only 28 per cent. in acuity. The amplification within the latter range of illumination is doubtless too great for feasibility of application. That is, too wide a range of illumination would have to be used to compensate for the difference between the resolving power in the poorest and best meridians in the ordinary run of astigmatisms. The range from 1–9 meter-candles is, however, quite feasible and the relation between the two scales gives abundant sensitivity. These values fall within the range given by the apparatus described in our former paper, 0.07–9.5 meter-candles. The testing of a large number of astigmatisms with this apparatus showed that in the majority of cases the minimum amount of light required for the discrimination of the opening in the broken circle (visual angle, 1 min.) in the most favorable meridian was of the order of 1–3 meter-candles; in the least favorable meridian, of the order of 6–9.5 meter-candles.

A very convenient apparatus for using the illumination scale for detecting low astigmatisms and small errors in the

[1] "Ueber die Beziehung zwischen der Sehschärfe und der Beleuchtungsintensität," *Verhandl. der Physikal. Ges. in Berlin*, 1885, 16, S. 79–83.

amount and placement of their corrections was described in a former number of this journal, "An Apparatus for Determining Acuity at Low Illuminations, etc.," 1920, Vol. III, No. 1, pp. 59–71. In this apparatus, it will be remembered, uniformity of illumination of the test surface was secured by

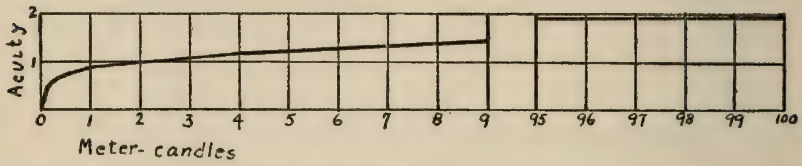

FIG. 1. Showing the relation of intensity of illumination to acuity (Koenig, 4 observers).

projecting upon it the image of an evenly illuminated aperture at the inner end of a projection tube of a lantern or lamp house. In order to secure a uniform illumination of this aperture, the lamp house was lined with opal glass ground on one side, and the aperature itself was covered with a slide of ground glass. The source of light was a round bulb, 100-watt, type C Mazda lamp with its filament well above the aperture to be illuminated, and the changes of illumination were produced by an iris diaphragm placed immediately behind the focusing lens in the projection tube, which reduced the illumination without changing the size or shape of the image. The test-object was a broken circle fastened at the center of a graduated dial the opening of which (visual angle, 1 minute) could be turned into any meridian that was desired. The angle of turning could be read in terms of the divisions on the dial which was graduated to correspond to the readings on the trial frames used in office and clinic work. The results given in this paper were obtained with this type of apparatus. They are fairly representative of the large number that have been obtained.

In the testing and demonstration of the sensitivity and serviceability of the illumination method for determining the exact amount and placement of the correction of an astigmatism the following types of material have been selected: (1) Artificial astigmatisms made with cylinders of low diopter

value. In choosing to include artificial astigmatisms in this work it should be understood that we did not consider the artificial astigmatism the precise functional equivalent of the natural astigmatism. We are too strongly impressed with the possibility that the astigmatic eye may progressively acquire power to compensate in part for its defect to be of this opinion. They were selected because we wished to have in one set of cases an exact knowledge of the amount and location of the defect as a check on the determinations made by the test. (2) Natural astigmatisms without a cycloplegic. (3) Office and clinic cases with a cycloplegic. The difference in result between the most and least favorable meridians or between a true and a false correction have thus far been of a considerably greater order of magnitude with than without a cycloplegic either in case of a natural or an artificial astigmatism. (4) Office and clinic cases, submitted to us by experienced refractionists, in which the apparatus has been used merely to check up corrections already made by the clinic methods, objective and subjective. Among these cases it was comparatively rare to find one in which the minimum amount of light required to discriminate the test-object in the corrected meridian was even approximately equal to that required in the other meridians. Indeed in some cases the difference between the most and least favorable meridian exceeded the range of variation obtainable with the apparatus when provided with the 100-watt lamp. And (5) irregular astigmatisms.

For the artificial astigmatisms three cases have been used.

1. *Low Astigmatisms Produced by Weak Cylinders.*—In this case the minimum amount of light required to discriminate the test-object with the opening of the circle turned into the most and least favorable meridians has been determined; also when turned 5, 10 and 45 degrees from the most favorable meridian. In Table I. it will be noted that in case of an astigmatism produced by a 0.25 diopter cylinder the difference in the light required for the discrimination of the test-object in the worst and best meridians amounted to 107.2 per cent. as an average result for five eyes. At 5 degrees from the

Table I

Sensitivity of Apparatus for Locating Meridian of Astigmatism

Astigmatisms produced by 0.25 and 0.75 diopter cylinders.

Observer	Value of Cylinder Producing Astigmatism	Minimum Illumination Required for Discrimination of Test-object (Meter-candles)					Difference in Results Between Best and Other Meridians							
							Meter-candles				Per Cent.			
		Best Meridian	5° from Best Meridian	10° from Best Meridian	45° from Best Meridian	Worst Meridian	5°	10°	45°	Worst Meridian	5°	10°	45°	Worst Meridian
A.......	0.25	0.60	0.88	1.49	1.62	1.62	0.28	0.89	1.02	1.02	46.7	148.3	170.0	170.0
B.......	0.25	1.12	1.75	2.405	2.69	2.69	0.63	1.285	1.57	1.57	56.3	114.7	131.5	131.5
C.......	0.25	0.46	0.60	0.76	0.76	0.76	0.14	0.30	0.30	0.30	30.4	65.2	65.2	65.2
D.......	0.25	1.42	2.115	2.49	2.49	2.49	0.695	1.07	1.07	1.07	48.9	75.4	75.4	75.4
E.......	0.25	1.12	1.88	1.95	2.17	2.17	0.76	0.83	1.05	1.05	67.9	74.1	93.8	93.8
Average.	....	....	....	....	....	....	0.501	0.875	1.002	1.002	50.0	95.5	107.2	107.2
A.......	0.75	1.30	2.69	3.05	3.05	3.05	1.39	1.75	1.75	1.75	106.9	134.6	134.6	134.6
B.......	0.75	1.81	4.11	4.39	4.39	4.39	2.30	2.58	2.58	2.58	127.8	142.5	142.5	142.5
C.......	0.75	0.60	1.75	1.95	2.32	2.32	1.15	1.35	1.72	1.72	191.7	225.0	286.7	286.7
D.......	0.75	3.05	6.895	6.895	7.60	7.60	3.845	3.845	4.55	4.55	126.1	126.1	149.2	149.2
Average.	....	....	....	....	....	....	2.171	2.381	2.65	2.65	138.1	157.1	178.3	178.3

best meridian, this difference was 50 per cent.; at 10 degrees, 95.5 per cent.; and at 45 degrees 107.2 per cent. In case of the 0.75 diopter astigmatism, the difference between the worst and best meridians was 178.3 per cent.; at 5 degrees from the best meridian, 138.1 per cent.; at 10 degrees, 157.1 per cent.; and at 45 degrees, 178.3 per cent.

2. *Small Errors in the Placement of the Correction.*—In Table II. it will be noted that in case of an astigmatism pro-

Table II

Sensitivity of Apparatus for Detecting Small Errors in the Placement of the Correction of an Astigmatism

Observer	Value of Cylinder Producing Astigmatism	Minimum Illumination Required for Discrimination of Test-object (Meter-candles)			Difference in Result for Correct and Incorrect Placements					
		Exact Placement of Correction	5° Displacement	10° Displacement	Scale Divisions		Meter-candles		Per Cent.	
					5°	10°	5°	10°	5°	10°
A	0.25	0.60	1.33	1.62	13.0	17.0	0.73	1.02	121.7	170.0
B	0.25	1.12	2.25	2.69	17.5	22.0	1.13	1.57	100.9	140.2
C	0.25	0.46	0.60	0.65	3.0	4.0	0.14	0.19	30.4	41.3
D	0.25	1.42	1.55	1.88	2.0	7.0	0.13	0.46	9.2	32.4
E	0.25	1.12	1.91	2.17	12.5	20.0	0.79	1.05	70.5	93.8
Average					9.6	14	0.58	0.86	66.5	95.5
A	0.75	1.30	2.49	3.05	17.0	22.0	1.19	1.75	91.5	134.6
B	0.75	1.81	3.43	4.39	17.0	22.0	1.62	2.58	89.5	142.5
C	0.75	0.60	1.42	2.12	14.0	24.0	0.82	1.52	136.7	253.3
D	0.75	3.05	6.44	6.44	20.0	20.0	3.39	3.39	111.1	111.1
Average					17.0	22.0	1.75	2.31	107.2	160.4

duced by a 0.25 diopter cylinder a displacement of the correction 5 degrees from the true position required 66.5 per cent. more light for the discrimination of the test-object as an average result for five eyes; a displacement of 10 degrees, 95.5 per cent. more light. In case of a 0.75 diopter astigmatism a displacement of 5 degrees required 107.2 per cent. more light; and a displacement of 10 degrees, 160.4 per cent. more light. In connection with this table note also the large number of scale divisions between the correct and the incorrect placement of the cylinder. In case of a 5 degree displacement for the 0.25 diopter astigmatism, this difference

averaged 9.6 for the five eyes. That is, since the diaphragm can be readily set to half divisions, 19 settings of the light control could have been made with precision between the values needed for the true correction and the 5 degree displacement. This shows that the sensitivity of the apparatus far exceeds the present possibilities of the precise manipulation of the correcting cylinders.

3. *Small Errors in the Amount of the Correction.*—In the case of a 0.12 diopter error in the correction of an astigmatism, 54.6 per cent. more light was required for the discrimination of the test-object in the worst meridian; in case of a 0.25 diopter error, 108.9 and in case of a 0.75 diopter error, 178.25 per cent. more light was required. These results are shown in Table III.

TABLE III

SENSITIVITY OF APPARATUS FOR DETECTING ERRORS IN THE AMOUNT OF CORRECTION OF AN ASTIGMATISM

Observer	Minimum Illumination Required for Discrimination of Test-object with Different Errors in Amount of Correction (Meter-candles)						Difference in Minimum Illumination to Discriminate Test-object in Most and Least Favorable Meridians					
	0.12 Diopter		0.25 Diopter		0.75 Diopter		0.12 Diopter		0.25 Diopter		0.75 Diopter	
	Best Meridian	Worst Meridian	Best Meridian	Worst Meridian	Best Meridian	Worst Meridian	Meter-candles	Per Cent.	Meter-candles	Per Cent.	Meter-candles	Per Cent.
A......	0.60	0.88	0.60	1.62	1.30	3.05	0.28	46.7	1.02	170.0	1.75	134.6
B......	1.12	2.17	1.12	2.69	1.81	4.39	1.05	93.8	1.57	140.2	2.58	142.5
C......	0.46	0.65	0.46	0.76	0.60	2.32	0.19	41.3	0.30	65.2	1.72	286.7
D......	1.42	1.75	1.42	2.49	3.05	7.60	0.33	23.3	1.07	75.4	4.55	149.2
E......	1.12	1.88	1.12	2.17	——	——	0.76	67.9	1.05	93.8	——	——
Average......	.....	.....	.....	.....	.....	.....	0.52	54.6	1.00	108.9	2.65	178.25

Of the large number of natural astigmatisms tested space will be taken here for the representation of only a few cases.

ASTIGMATISM (WITHOUT A CYCLOPLEGIC)

Case I. (Age 13 Years)

O.D.: Correction by clinic methods, 0.25 cyl., ax. 70°. (Placement of axis could be varied over a range of about 45° and cylinder could be changed to 0.12 diopter without notice-

able change in the results by these methods.) With this correction illumination required with opening of the circle in meridian of cylinder axis, 0.20 m.c.; at 90 degrees from this position, 0.55 m.c.; difference, 0.35 m.c. or 175 per cent.

Correction by illumination method, + 0.12 cyl., ax. 55°. With this correction equal illumination (0.16 m.c.) was required for the discrimination of the test-object in all meridians.

Difference in amount of light required for discrimination of test-object in least favorable meridian for the two corrections, 0.39 m.c. or 244 per cent.

O.S.: Correction by clinic methods, + 0.12 cyl., ax. 180°. (Placement of axis could be varied over a range of about 45 degrees without change in result by these methods.) With this correction illumination required with opening of circle in meridian of cylinder axis, 0.12 m.c.; at 90 degrees from this position, 0.21 m.c.; difference, 0.09 m.c. or 75 per cent.

Correction by illumination method, + 0.12 cyl., ax. 15°. With this correction equal illumination (0.105 m.c.) was required for discrimination of test-object in all meridians.

Difference in amount of light required for discrimination of test-object in least favorable meridian for the two corrections, 0.105 m.c. or 100 per cent.

Case II. (*Age 48 Years*)

O.D.: Illumination required before correction with opening of circle in most favorable meridian, 2.93 m.c.; at 90 degrees from this position, 9.19 m.c.; difference, 6.26 m.c. or 214 per cent.

Correction by illumination method, − 0.50 cyl., ax. 105°. With this correction, equal illumination (2.93 m.c.) was required for the discrimination of the test-object in all meridians.

O.S.: Illumination required before correction with opening of circle in most favorable meridian, 2.35 m.c.; at 90 degrees from this position, 5.25 m.c.; difference, 2.90 m.c. or 123 per cent.

Correction by illumination method, + 0.37 cyl., ax. 137°. With this correction, equal illumination (2.35 m.c.) was re-

quired for the discrimination of the test-object in all meridians.

Irregular Astigmatism

Case I. (Age 32 Years)

O.S.: Illumination required with opening of circle turned right, left, and down, 0.97 m.c.; when turned up, 5.25 m.c.; difference for two halves of vertical meridian, 4.28 m.c. or 441 per cent.

Astigmatism (with Cycloplegic)

Case I. (Age 25 Years)

O.D.: Correction by clinic methods, + 0.50 S., + 0.37 cyl., ax. 15°. With this correction, illumination required with opening of circle in meridian of cylinder axis, 2.46 m.c.; at 90 degrees from this position, 9.19 m.c.; difference, 6.73 m.c. or 274 per cent.

Correction by illumination method, + 0.50 S., + 0.37 cyl., ax. 30°. With this correction, equal illumination (1.61 m.c.) was required for the discrimination of the test-object in all meridians.

Difference in amount of light required for discrimination of test-object in least favorable meridian for the two corrections, 7.58 m.c. or 471 per cent.

Case II. (Age 35 Years)

O.D.: Corrections by clinic methods, − 0.62 cyl., ax. 180°. With this correction, illumination required with opening of circle in meridian of cylinder axis, 2.32 m.c.; at 90 degrees from this position, 9.19 m.c.; difference, 6.87 m.c. or 296 per cent.

Correction by illumination method, − 0.75 cyl., ax. 180°. With this correction, equal illumination (2.09 m.c.) was required for the discrimination of the test-object in all meridians.

Difference in amount of light required for discrimination of test-object in least favorable meridian for the two corrections, 7.10 m.c. or 339 per cent.

Astigmatism (Checking Up of Glasses)

Case I. (Age 42 Years)

O.D.: Correction by clinic methods, − .50 S., − .37 cyl. ax. 10°. With this correction, illumination required with opening of circle in meridian of cylinder axis, 2.34 m.c.; at 90 degrees from this position, 7.35 m.c.; difference, 5.01 m.c. or 214 per cent.

Case II. (Age 45 Years)

O.D.: Correction by clinic methods, − 0.25 S., − 0.50 cyl., ax. 125°. With this correction, illumination required with opening of circle in meridian of cylinder axis, 2.02 m.c.; at 90 degrees from this position, 6.67 m.c. in one half of meridian, 7.82 m.c. in other half; difference, 4.65 m.c. (230 per cent.) and 5.80 m.c. (287 per cent.). Astigmatism may be slightly irregular.

O.S.: Correction by clinic methods, − 0.50 cyl., ax. 80°. With this correction, illumination required with opening of circle in meridian of cylinder axis, 0.97 m.c.; at 90 degrees from this position, 5.62 m.c. in one half of meridian, 6.23 m.c. in other half; difference, 4.65 m.c. (479 per cent.) and 5.26 m.c. (542 per cent.). Astigmatism may be slightly irregular.

In the above notes on cases we have, for the sake of brevity, used the term clinic methods, instead of specifying in greater particular the tests employed. Where we have made the comparison ourselves between the illumination method and the methods ordinarily employed in office and clinic work, we have used the acuity method, the astigmatic charts, the point of light test and in some cases the ophthalmometer. We have not made frequent use of the retinoscope because of the need of a cycloplegic. The acuity method was used in different ways. In one, patterned after a procedure much employed by the ophthalmologists, some character difficult of discrimination and taxing the resolving power of the eye in as many meridians as possible, such as the letter B, was selected. It was brought to or near to the threshold of discrimination by fogging, by changing the visual angle, by

the use of a graded scale of illumination, etc., in order to make the conditions favorable for a sensitive judgment; and the strength and placement of cylinder was determined which gave the maximum clearness of seeing. In order to decide between doubtful determinations other acuity tasks or tests were imposed. That is, we not only used the acuity test as employed by the practitioner but have endeavored in many ways to add to its sensitivity and precision without sacrificing its distinctive features. However, in collecting the data for the comparison we have preferred to lay the chief stress on the cases in which the clinic testing has been done by practicing ophthalmologists, who have very willingly given us their cooperation, In all cases but one, which have been submitted to us for testing, the physician has himself accompanied the patient, looked after the cycloplegia, and inspected the test procedure at every step, the principle of the apparatus and method having previously been made familiar to him. Due care was taken on both sides that a fair comparison of sensitivities was made.

Doubtless the apparatus can be used in different ways depending upon the experience and preference of the operator. For example, the minimum amount of light required to discriminate the test-object could be determined for one meridian and the setting of the light control be held constant while the test-object is rotated into the different meridians, the observer being required to judge in each case whether the same or more or less light would be required for its discrimination. This would serve as a rough indication of whether or not the eye is astigmatic. The exact meridian of the defect, that is the meridian in which the greatest amount of light is required to discriminate the opening in the circle, could be determined through a series of settings of the test-object and the light control. The placement of the correction having been determined, its amount could be found by the strength of cylinder required to render the minimum illumination needed to discriminate the test-object the same for all meridians, or more roughly speaking for the meridian of the defect and at 90 degrees either way from this position. A quicker and more

feasible method, however, is first to make an approximate determination of the amount and placement of the correction by the clinic methods and employ the illumination method only for a more precise determination. In using this method as a refinement on the clinic methods, the procedure we ordinarily employ is as follows: The patient's eye is fitted with a cylinder of the strength and placement indicated by the clinic tests and the minimum amount of light required to discriminate the opening in the circle is determined in four positions, two in the meridian of the cylinder axis and two in the meridian at right angles to this. If the minima are not equal in these four positions, the cylinder axis is shifted and the determinations are made again, the four positions of the opening of the circle always being in the meridian of the cylinder axis and the meridian at 90 degrees from it. If no placement of the cylinder is found which gives equal minima for the four positions, the strength of the cylinder is changed. The strength and placement of cylinder which requires both equal and the smallest amounts of light for the four positions of the test-object is accepted as the final correction.

The apparatus can also be used to advantage with astigmatic charts of the sunburst type, the radial lines of which are no more than 5 degrees apart, in the preliminary approximate determination of the axis of the defect. In this case the procedure would be to reduce the illumination until only one or perhaps two of the lines stand out clearly. This would give a sensitivity roughly speaking of about 5 degrees, and requires little more time than is usually consumed in the use of the astigmatic charts.

In our own work we have found that the apparatus would be very helpful even if it were used only to check up the corrections made by the clinic methods and were not employed further as an aid in finding out the exact amount and placement of the correction. For example, but a very few minutes are required to determine with it whether any given correction equalizes or levels up the resolving power of the eye in the different meridians. The advantage of a checking method which is definite and at the same time feasible,

can readily be appreciated by any one who has tried to decide by the clinic methods in any wide range of cases just what should be the exact amount and placement of the correction of an astigmatism. The method has its chief value perhaps in those cases in which it is particularly difficult to make a decision by the clinic methods, that is, in determining the exact amount of the correction in cases of high astigmatism and both the amount and placement of correction in case of low astigmatisms. The simple character of the judgment, namely the mere indication of the direction in which the opening of the circle points instead of the more difficult task of deciding under the comparatively rough conditions of the office and clinic test whether this or that placement or strength of cylinder gives the clearer vision, together with the objective check on the correctness of each judgment, also contribute to make the method especially valuable in case of children, and the subjective, unintelligent and untrained type of adult. A further advantage of the method as worked out in connection with the present apparatus is its great sensitivity for the detection of irregular astigmatisms. The lack of satisfactory tests for this troublesome defect is generally conceded.

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A STUDY OF OCULAR FUNCTIONS WITH SPECIAL REFERENCE TO THE LOOKOUT AND SIGNAL SERVICE OF THE NAVY

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The incentive for this work was the need for establishing a system of testing for those branches of service in the Navy requiring especially keen scotopic or low illumination acuity. The first step towards the accomplishment of this purpose was the devising of a suitable apparatus and test method. The request for an apparatus came to us from the head of the Eye Division of the United States Naval Hospital at Washington. The apparatus was described in a former paper, "An Apparatus for Determining Acuity at Low Illuminations, etc.," this JOURNAL, 1920, III., pp. 59–71. A further need was to find out what range of difference in scotopic acuity might be expected among eyes graded as fit on the basis of the tests of other functions and capacities. A consideration of this need has led us to make a preliminary survey of eyes graded as normal with regard to photopic acuity and other commonly tested functions in order to determine whether such eyes may be expected to show a significant difference in keenness of functioning at low illuminations.

In a thorough test for vocations requiring keenness of discriminations at low illuminations, the following points should be taken into account: (1) the minimum amount of light required to discriminate the test-object before adaptation; (2) the minimum amount after a properly selected period of adaptation; and (3) the rapidity as well as the amount of gain in acuity in the process of adapting. Determinations covering all of these points have been made in this study.

The Range of Illumination Required by Normal Eyes for the Discrimination of the Standard Test Object

In making these determinations three test-objects were used: the Snellen chart and two single test-objects which could be rotated into different positions—the letter E and the international test-object, the broken circle, each subtending a 5-min. angle. In case of the latter two, the task required of the observer was to indicate roughly the direction in which the opening in the test character was turned, an objective check being had on the correctness of the judgment. The determinations were made at the beginning and end of a 45-min. adaptation period. It is obvious that the results at low illumination should be influenced by the refraction condition of the eye as well as by its light sensitivity and the individual differences in the effect of light sensitivity on acuity. In order that the observers could be chosen so that the results would represent the differences which may occur among eyes having normal or better than normal photopic acuity, each eye was refracted and the acuity was taken under 5 foot-candles (53.8 meter-candles) of light. In the first series of tests 22 observers were used ranging from 18 to 28 years of age. Results were obtained for both eyes and for each eye separately. Of the eyes used, 75.7 per cent. would be rated in the Snellen scale as having 6/4 acuity; 13.5 per cent. as having 6/5 acuity; and 10.8 per cent. as having 6/6 acuity. It was our intention to use throughout only eyes which could be ranked as Grade A with regard to photopic acuity.

The results of these determinations show a greater range of individual difference for the broken circle than for the Snellen chart or the letter E (905 per cent. for the broken circle, 548 per cent. for the letter E and 357 per cent. for the Snellen chart). This superior showing for the broken circle is perhaps in accord with the general finding that the broken circle as a test-object picks up smaller differences in acuity than either of the other two test-objects employed. These differences too, it will be remembered, are amplified in the

present case by the fact that they are read on the illumination scale—an amplifying scale—and not on a scale which sustains a 1 : 1 relation to acuity. Inasmuch as the greater sensitivity was shown in these preliminary experiments by the broken circle as a test-object, 15 additional observers (photopic acuity, 6/4) were employed using this test-object alone.

Space will be taken here only for a brief general statement of the results for this latter series of determinations alone. (1) The individual differences in the minimum illumination required for the discrimination of the test-object before the period of dark adaptation fell between 0.70 and 5.29 meter-candles, a range of 657 per cent.; after the period of dark adaptation it fell between 0.32 and 2.2 meter-candles, a range of 593 per cent. A greater range of individual difference, it will be noted, was found for the tests taken before the period of dark adaptation than for those taken after the 45-minute adaptation period. This was doubtless in part due to the lack of careful standardization of the initial sensitivity by a period of preadaptation to light of a fixed intensity and to small individual differences in photopic acuity revealed by the more sensitive method of testing; and in part to individual differences in the amount and rate of adaptation. A careful initial standardization of sensitivity was purposely avoided in this preliminary work with the apparatus in order more closely to approximate the rough conditions of testing which are apt to prevail in the selection of men with reference to vocational fitness. The results of these determinations are shown in Table I.

(2) Thus far without exception the two eyes of the same observer have required a different amount of light just to discriminate the test-object. This difference has ranged after adaptation from 19 to 54 per cent. of the amount of light required for the better eye.

(3) A question is often raised with reference to points of advantage of binocular as compared with monocular seeing. In 6 per cent. of the number of cases tested, the binocular result after adaptation was equal to or approximated the result for the poorer eye; in 88 per cent. of the cases it was better

Table I

Showing the Amount of Light Required just to Discriminate the Test-object at the Beginning of Dark Adaptation and at the End of 15, 30 and 45 Minutes (15 Observers)

In these experiments there was no standardization of the initial sensitivity by a previous adaptation to an illumination of constant intensity.

Observer	Photopic Acuity	Illumination in Meter-candles Required Just to Discriminate the Test-Object				Difference in Illumination Required at Beginning and at End of 45 Minutes	
		Beginning	At End of 15 Min.	At End of 30 Min.	At End of 45 Min-	Meter-candles	Per Cent.
G.......	6/4	0.70	0.55	0.35	0.32	0.38	118.8
M......	6/4	1.00	1.00	0.82	0.82	0.18	21.9
Mc......	6/4	1.24	1.00	1.00	1.00	0.24	24.0
R.......	6/4	1.36	0.60	0.50	0.60	0.76	126.7
L.......	6/4	1.55	1.00	0.88	0.88	0.67	76.1
S.......	6/4	1.75	1.42	0.88	0.88	0.87	98.9
Th......	6/4	2.11	0.82	0.94	0.94	1.17	124.5
Y.......	6/4	2.11	1.55	1.49	1.42	0.69	48.6
St......	6/4	2.40	0.60	0.60	0.60	1.80	300.0
Sw......	6/4	3.43	2.17	2.20	2.20	1.23	55.9
K.......	6/4	3.90	2.81	2.40	2.10	1.80	85.7
T.......	6/4	3.97	1.18	0.82	0.88	3.09	351.1
Sm......	6/4	4.10	3.80	1.40	1.30	2.80	215.4
W.......	6/4	4.20	1.40	0.76	0.76	3.44	452.6
Ba......	6/4	5.29	2.11	2.02	2.11	3.18	150.7

than the result for either eye; and in the remaining 6 per cent. of the cases it was intermediate to the results obtained with the two eyes separately. In none of the cases tested separately was it equal or approximately equal to the result for the better eye. In the 88 per cent. of cases referred to, less light was required for the discrimination of the test-object by the two eyes than by the better eye alone by amounts ranging from 14.5 to 67.3 per cent.

In order to get a rough idea of the grouping of the 15 observers with reference to the minimum amount of light required to meet the standard of acuity imposed by the test, before and after the period of dark adaptation, they have in each case been divided into six equally spaced groups, each group for the work before adaptation covering a range of 1 meter-candle and for the work after adaptation a range of 0.4 meter-candle. For the tests before adaptation 13.3 per cent. fall in the first or best group; 26.7 per cent. in the second group; 20 per cent. in the third group; 20 per cent.

in the fourth group; 13.3 per cent. in the fifth group; and 6.7 per cent. in the sixth group. For the tests after adaptation 6.7 per cent. fall in the first group; 20 per cent. in the second group; 40 per cent. in the third group; 13.3 per cent. in the fourth group; none in the fifth group; and 20 per cent. in the sixth group. A graphic representation of this grouping is shown in Fig. 1.

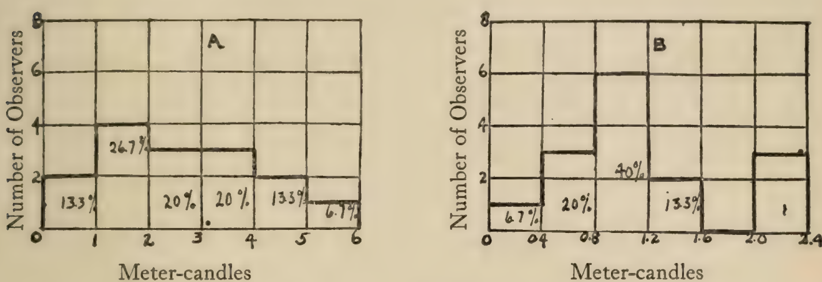

Fig. 1. Representing the relative distribution of 15 observers graded with reference to the minimum illumination required just to discriminate the test-object: *A*, before adaptation; *B*, after a 45-minute period of dark adaptation.

Individual Variations in the Amount and Rate of Adaptation in Terms of Effect on Acuity

The preceding experiments furnish data with regard to the minimum amounts of light required just to discriminate the different test-objects at the beginning and end of the 45-minute adaptation period. In case of the 15 observers tested with the broken circle in the final series of experiments at the beginning of dark adaptation and at the end of 15, 30 and 45 minutes, the minimum difference in this amount of light was 0.18 meter-candle or 22 per cent. of the amount required at the end of the adaptation period; the maximum difference was 3.44 meter-candles or 452.6 per cent. of the amount required at the end of the adaptation period. These results are shown in Table I.

In addition to these experiments a special adaptation series was run in which the minimum illumination required just to discriminate the test-object was determined at the

beginning of the adaptation period and at the end of 5, 10, 15, 25, 35 and 45 minutes. In order to standardize the initial sensitivity of the eyes of the observer, a preadaptation period of 20 minutes was given to 80 foot-candles of light (vertical component), the skylight illumination of an optic's room on a medium bright day. A few of the results obtained are represented in Table II. and Fig. 2. These results, it will be remembered, represent adaptation only as it affects acuity, which is the effect of greatest importance to the special work for which the apparatus was devised and the effect with which we are the most concerned for the greater part of our working lives. A comparison of these results with those of similar

Table II

Showing the Amount of Light Required just to Discriminate the Test-object at the Beginning of Dark Adaptation and at the End of 5, 10, 15, 25, 35, and 45 Minutes (6 Observers)

In these experiments the initial sensitivity was standardized by 20 minutes preadaptation to 80 foot-candles of light (vertical component), the illumination of a skylight optics room on a medium bright day.

Observer	Photopic Acuity	Illumination in Meter-candles Required Just to Discriminate the Test-object							Difference in Illumination Required at Beginning and at End of 45 Minutes	
		Beginning	At End of 5 Min.	At End of 10 Min.	At End of 15 Min.	At End of 25 Min.	At End of 35 Min.	At End of 45 Min.	Meter-candles	Per Cent.
I...	6/4	0.55	0.505	0.42	0.35	0.32	0.35	0.35	0.20	57.1
II...	6/4	0.705	0.42	0.42	0.32	0.32	0.32	0.38	0.325	85.5
III...	6/4	1.06	0.76	0.60	0.46	0.35	0.46	0.46	0.60	130.4
IV...	6/4	1.12	0.82	0.52	0.32	0.32	0.38	0.38	0.74	194.7
V...	6/4	1.62	1.12	0.94	0.55	0.60	0.60	0.55	1.07	194.5
VI...	6/4	2.20	1.12	1.14	1.18	1.36	1.24	1.24	0.96	77.4

series in which the object is to measure the increase in light sensitivity as a result of dark adaptation shows that just as acuity increases slowly with increase of illumination (except at very low illuminations) so also does it increase slowly with increase of sensitivity to light. That is, the eye does not gain in acuity by adaptation nearly so fast as it gains in light sensitivity.

In Fig. 2 the actual amounts of illumination required just to discriminate the test-object are plotted against time of

adaptation. It thus affords a comparison of the position of the minima of the different observers in the illumination scale and comprehends data from which the following points can be determined: (*a*) their relative ranking with regard to

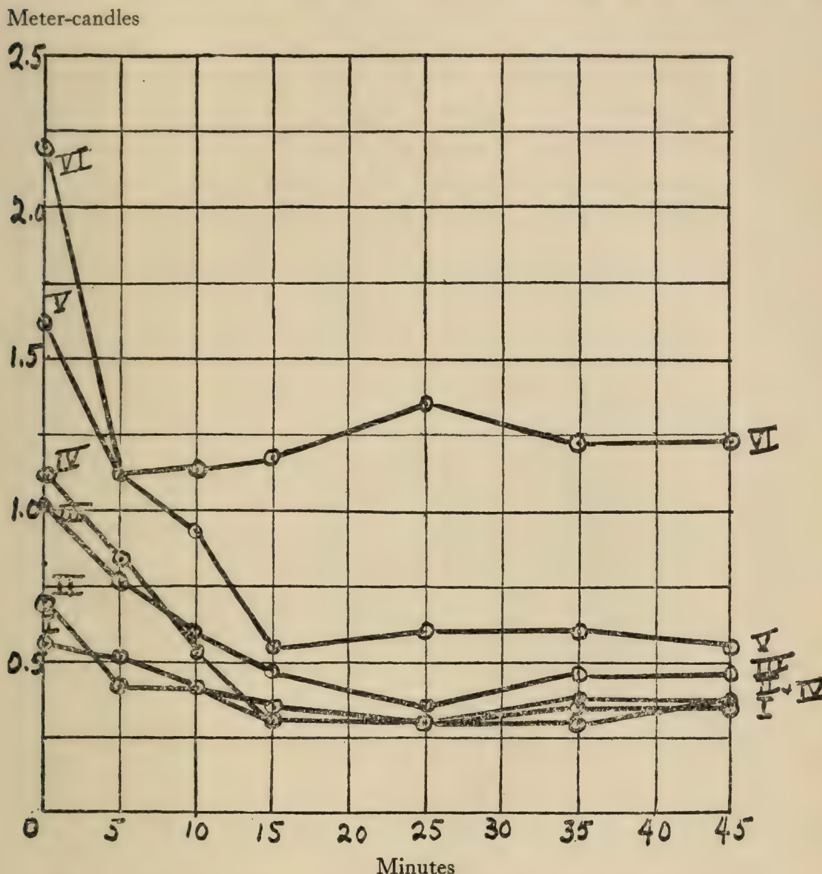

FIG. 2. Curves showing the decrease in the amount of light required just to discriminate the test-object as the result of dark adaptation. In order to standardize the initial sensitivity, the eye was preadapted in each case for 20 minutes to 80 foot-candles of illumination (vertical component).

scotopic acuity before and after adaptation, rated on the illumination scale; (*b*) their light sensitivity before and after adaptation insofar as it affects the minimum amounts of light required to discriminate the test object; and (*c*) their relative amounts of change in sensitivity, measured in terms of effect

on acuity, read on the illumination scale, due to adaptation. All of these features are important for vocational and clinic classification. In order to make these results more directly comparable with reference to the last of these points, namely

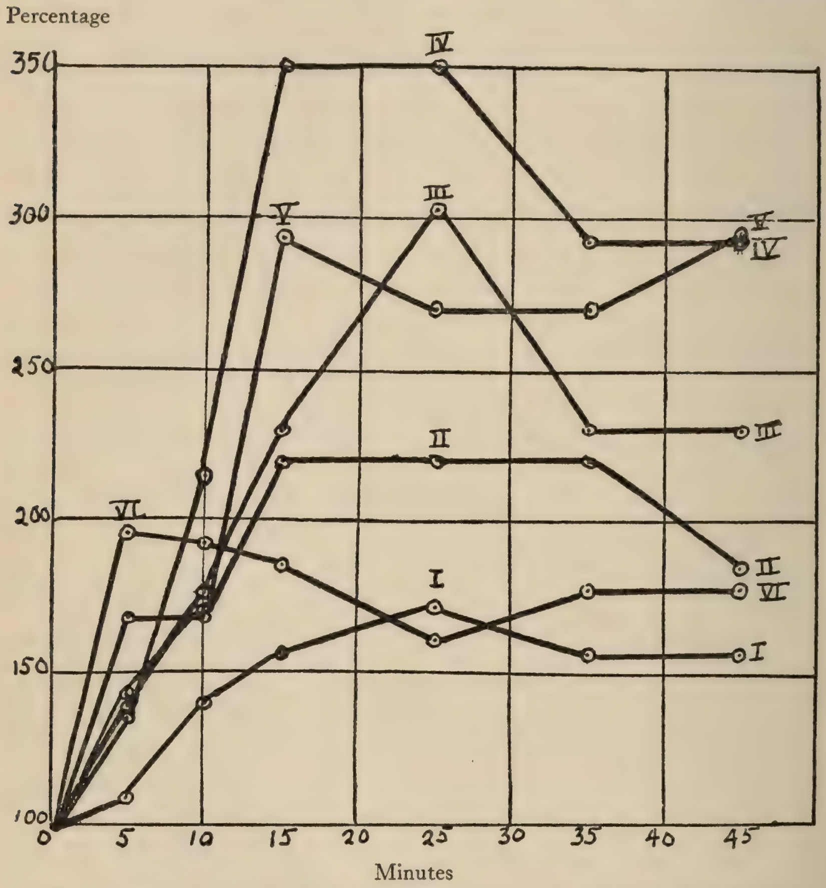

Fig. 3. Curves showing the increase in sensitivity as the result of dark adaptation, the reciprocal of the amount of light required just to discriminate the test-object being taken as the measure of sensitivity. Percentage increase in sensitivity is plotted against time of adaptation. The initial sensitivity of the eye was standardized in each case by 20 minutes of preadaptation to 80 foot-candles of light, vertical component.

relative amounts of change in sensitivity due to adaptation, the ratios or percentages of increase in sensitivity are plotted in Fig. 3, the reciprocals of the minimum amounts of light required just to discriminate the test-object being taken as

the measure of sensitivity. That is, the ratio or percentage change in the value of these reciprocals is plotted against time of adaptation, the curves beginning at a common point or unit ratio. The relative ratings with regard to the second point could of course be represented by plotting the reciprocals themselves. Space will not be taken here for this representation.

It will be noted that the greater part of these observers reach their maximum acuity at the end of 15 minutes of adaptation and that some even show a lower acuity if the series is continued beyond this time. The loss in the latter case is doubtless due to fatigue of the muscles of adjustment. That is, in case of the observers more susceptible to muscle fatigue, the loss of acuity due to fatigue more than compensated for the small gain in light sensitivity after the first 15–25 minutes. In this connection it may be noted that the muscle strain imposed by taking the acuity at the minimum illumination is much greater than at the illuminations ordinarily used. Even with a 5–10 minute rest period between determinations and a 2-second interval between the individual observations making up one determination, a very noticeable fatigue was present at the end of the 45-minute series.

In testing fitness for the lookout and signal service work of the Navy, night flying, and for other work and vocations that require the keen discrimination of objects when small amounts of light enter the eye, it was deemed better to make the tests in terms of acuity rather than of the light sense. Retinal sensitivity is only one of the factors in the eye's power to see its objects at low illuminations. For example, we frequently find observers with an excellent light sense whose scotopic acuity or power to discriminate objects at low illuminations is poor. Indeed, as shown in this and former papers, slight differences in resolving power correspond to relatively large differences either in illumination (except for very low illuminations) or retinal sensitivity in their effect on the eye's power to see clearly at low illuminations. Any test therefore for fitness for tasks or work requiring the power to see clearly at low illuminations is far from complete which

leaves out of account resolving power and the varying effect of changes in illumination or in light sensitivity on acuity. The acuity test, on the other hand, includes all of the factors involved in seeing and in the exact proportions in which they are contributory to seeing. Moreover, it is much better directly to determine the candidate's power to see clearly at low illuminations than to try to infer this from a light sense test and data on acuity taken at higher illuminations. This was, we may say, also the point of view of the Naval authorities under the auspices of whom we undertook to devise an apparatus suitable for testing acuity at low illuminations.

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